Observations of Strong Alfvén Waves in the Solar Chromosphere

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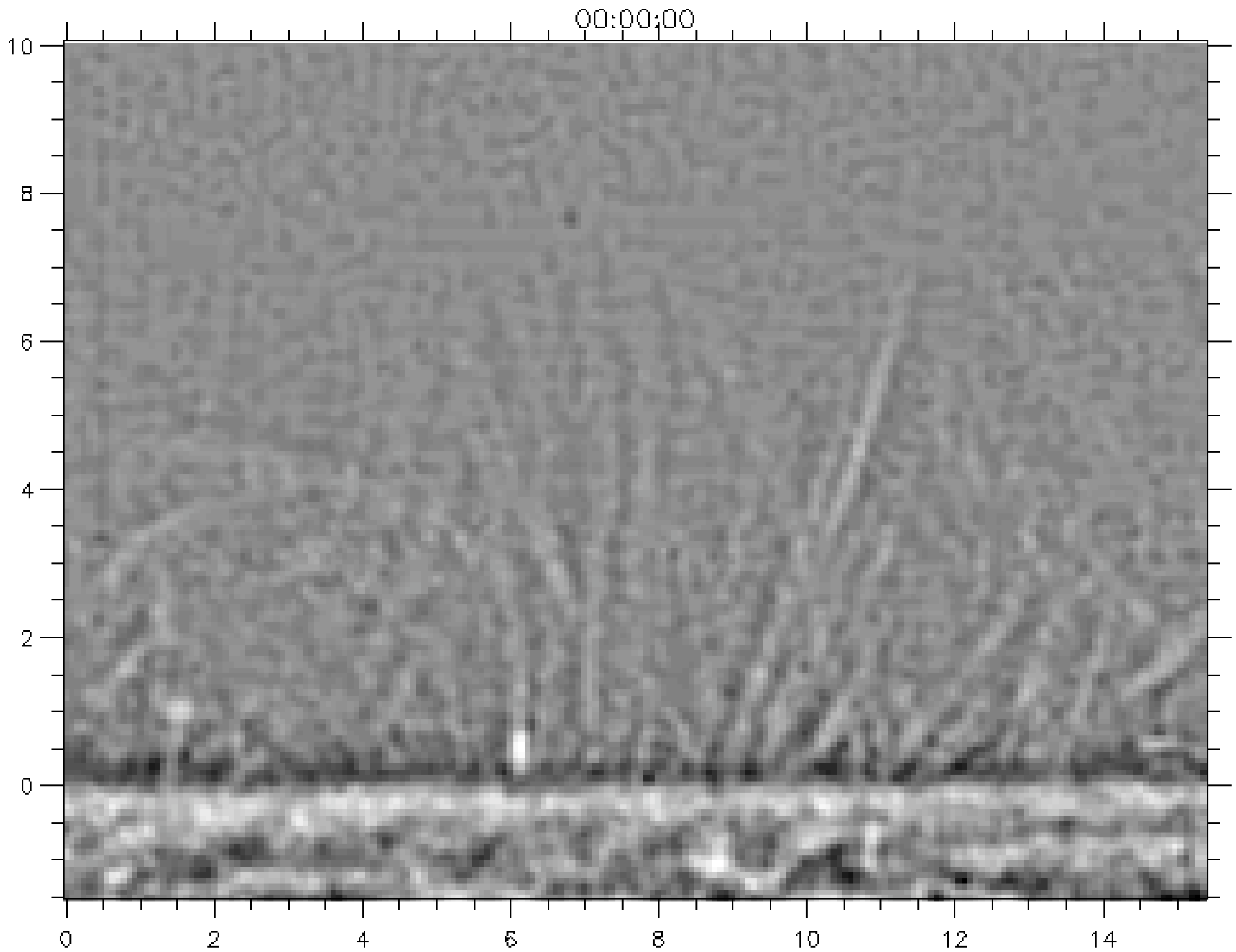
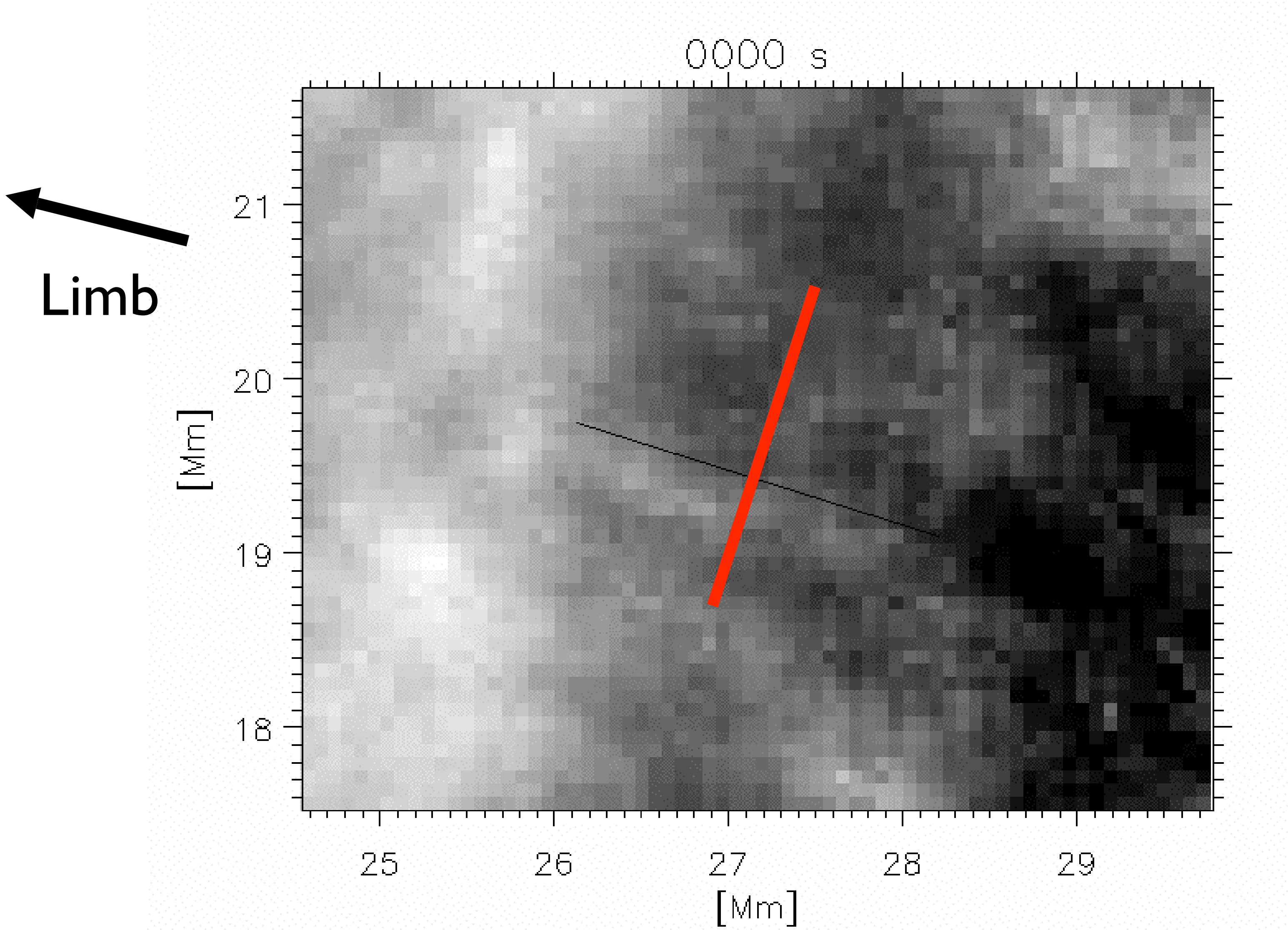
Unsharp Masked Ca II H movie of Coronal Hole from Hinode

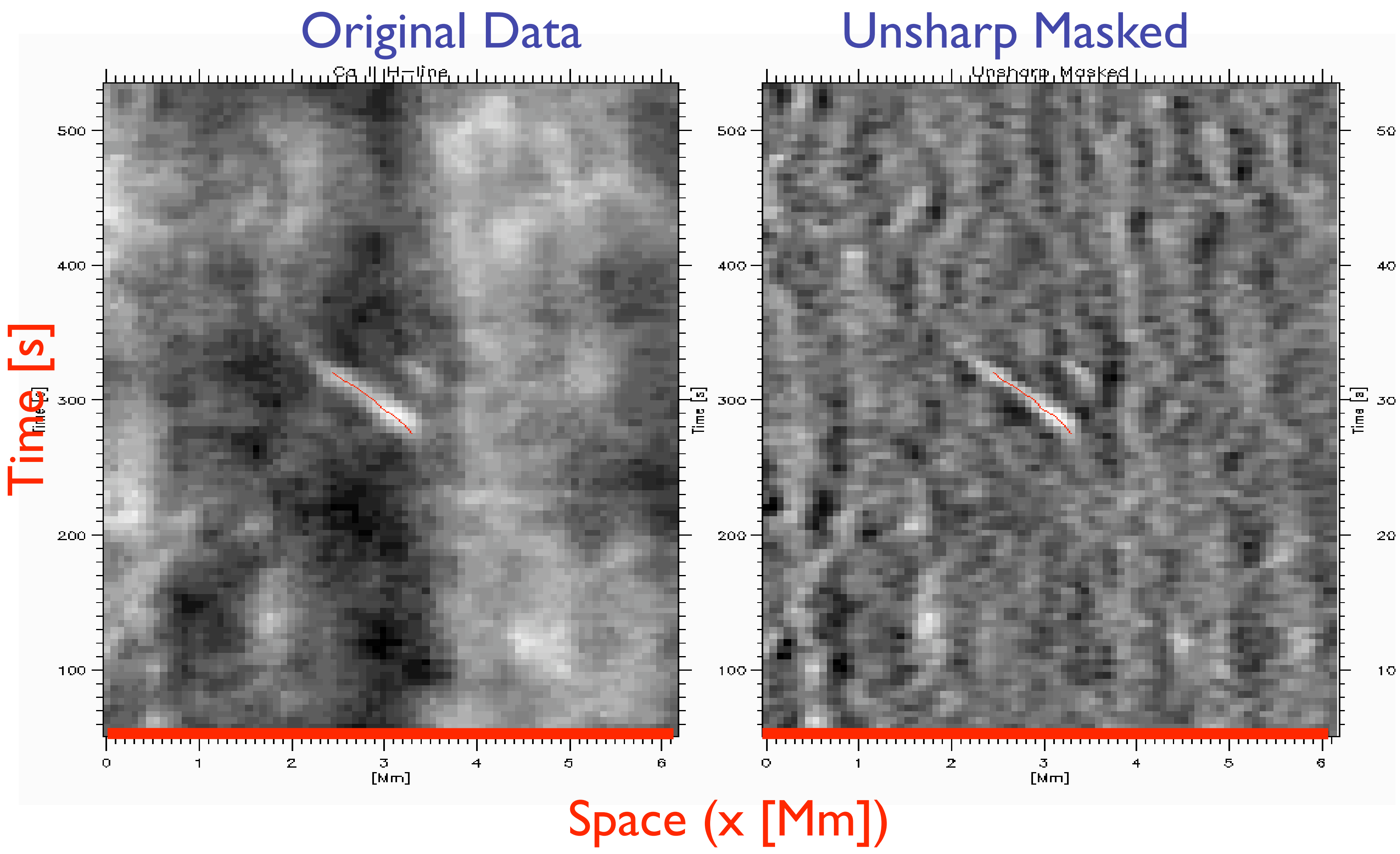


Chromosphere is dominated by short-lived (10-60 s),
thin (~200 km) jets or "straws" that undergo "lots of swaying"!

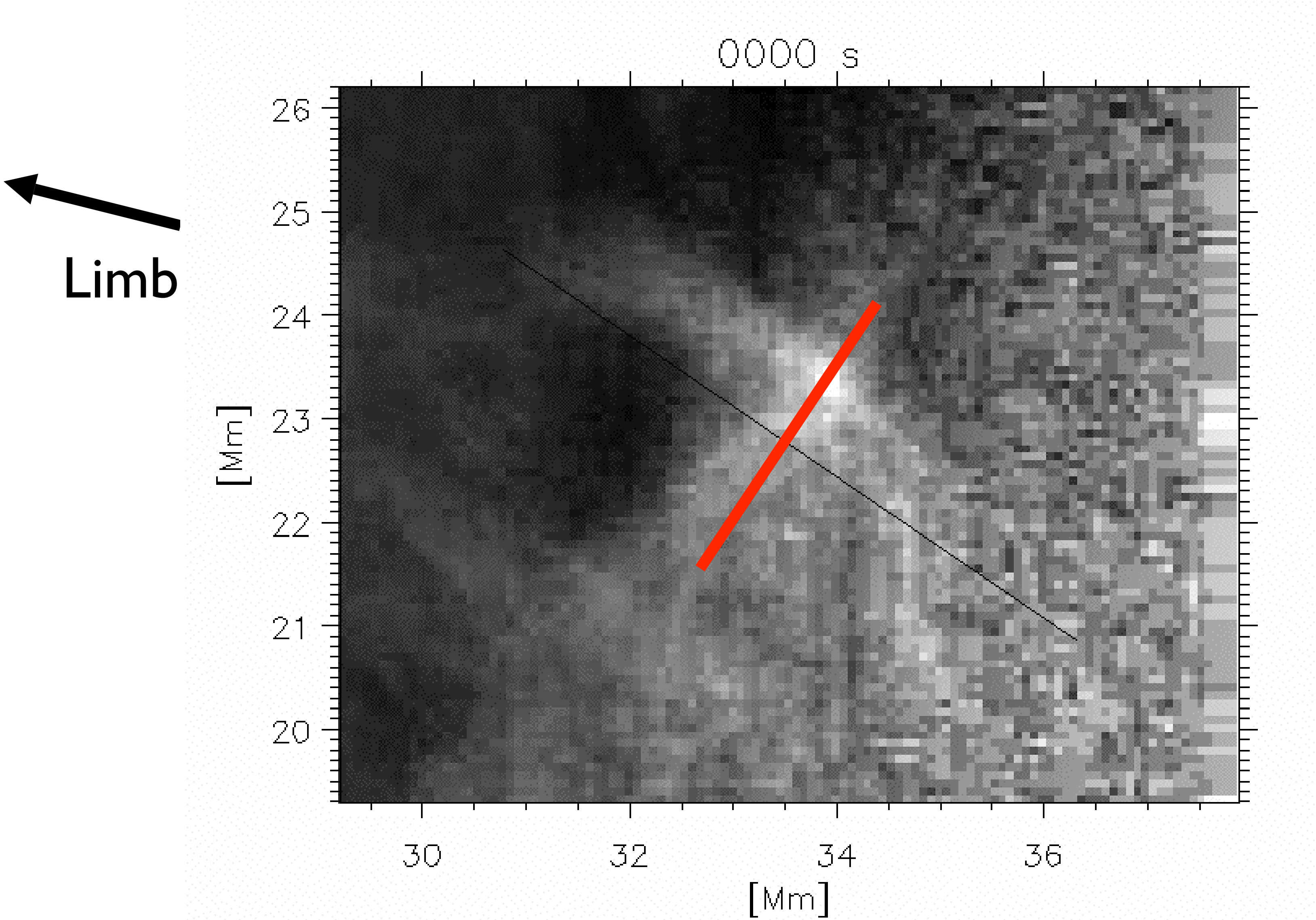
Most jets undergo significant transverse motion



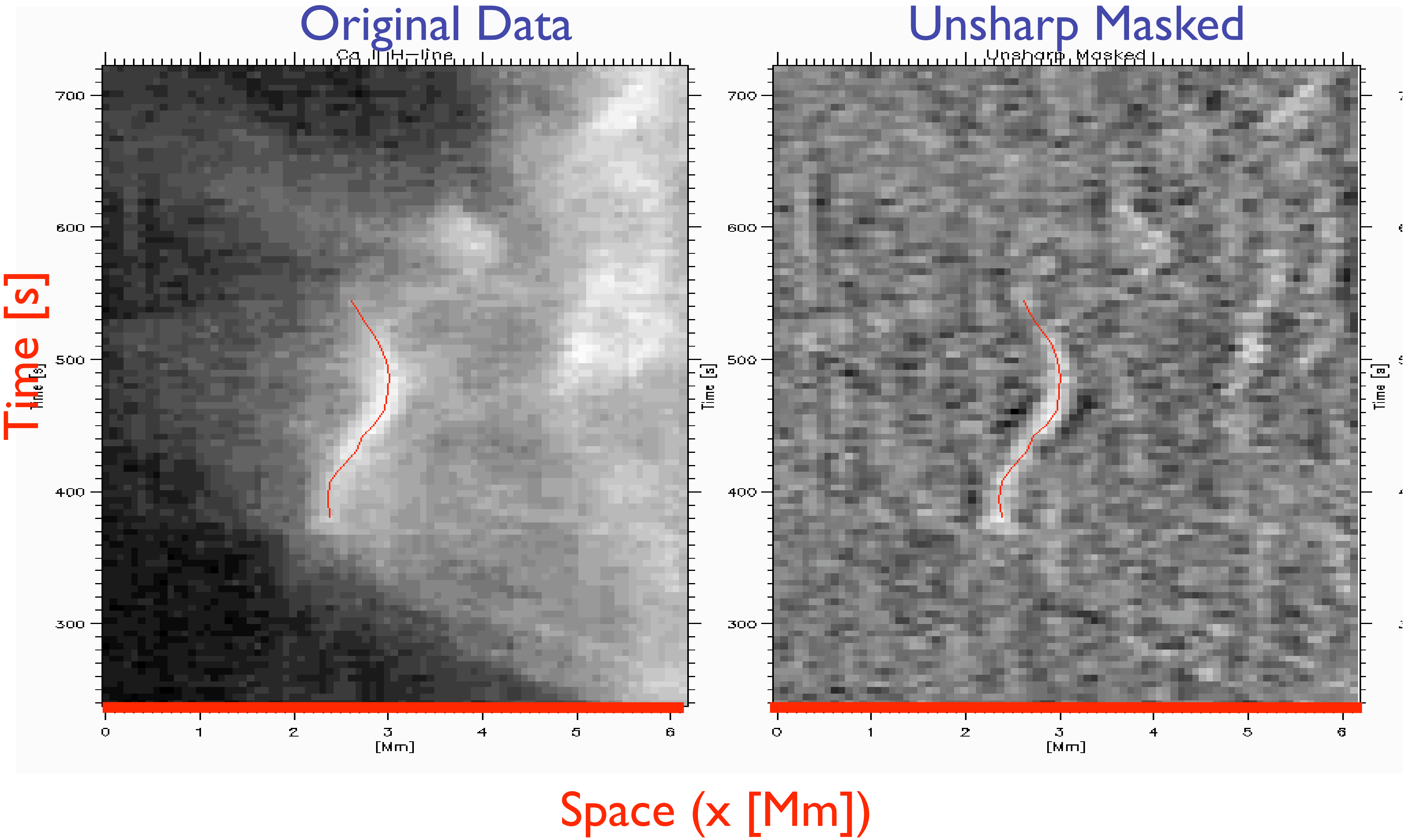
xt-cut from movie shows almost linear motion followed by fading



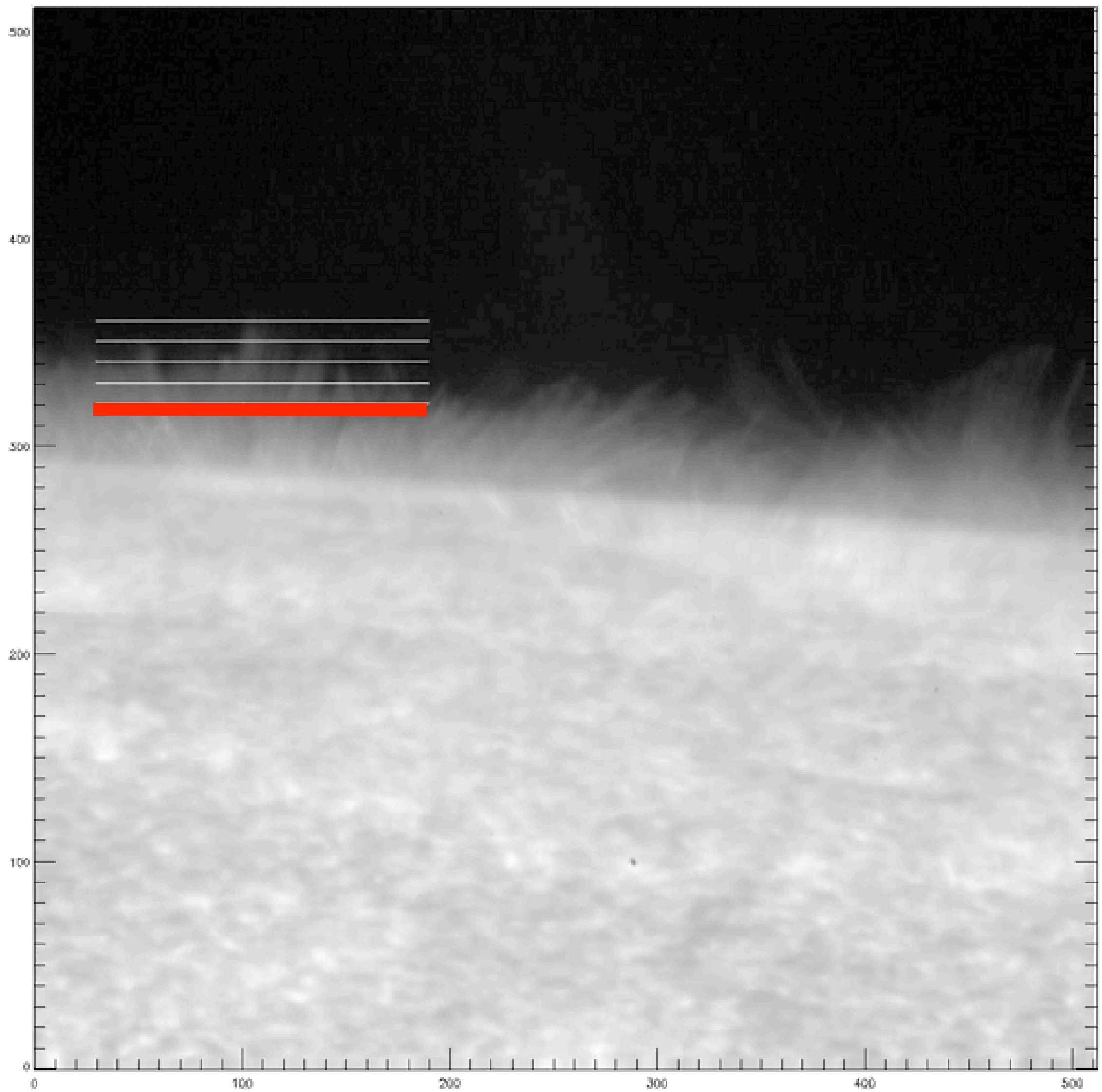
Many jets undergo “oscillatory” transverse motion



xt-cut from movie shows swaying motion followed by fading



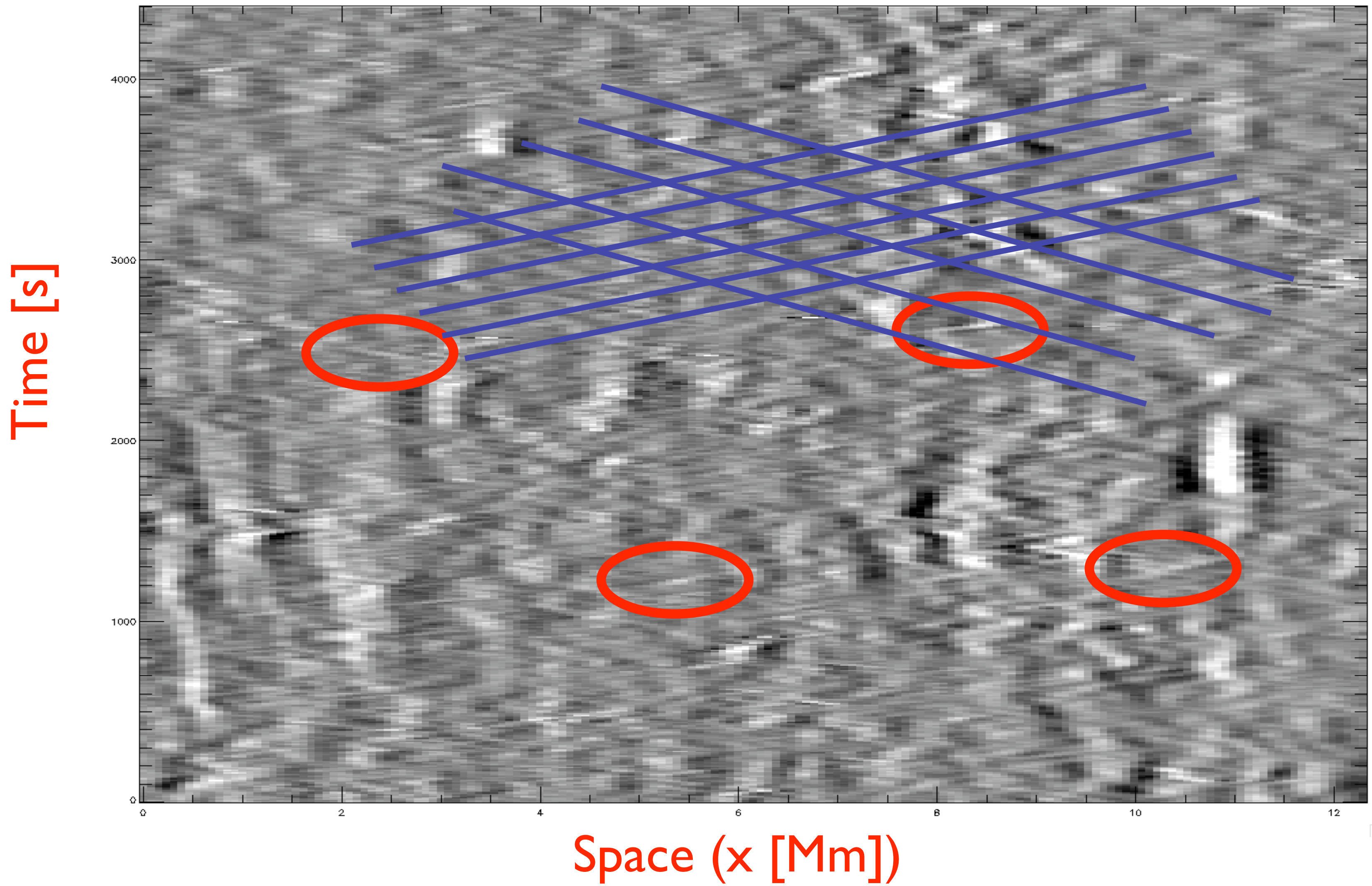
How general is this behavior?



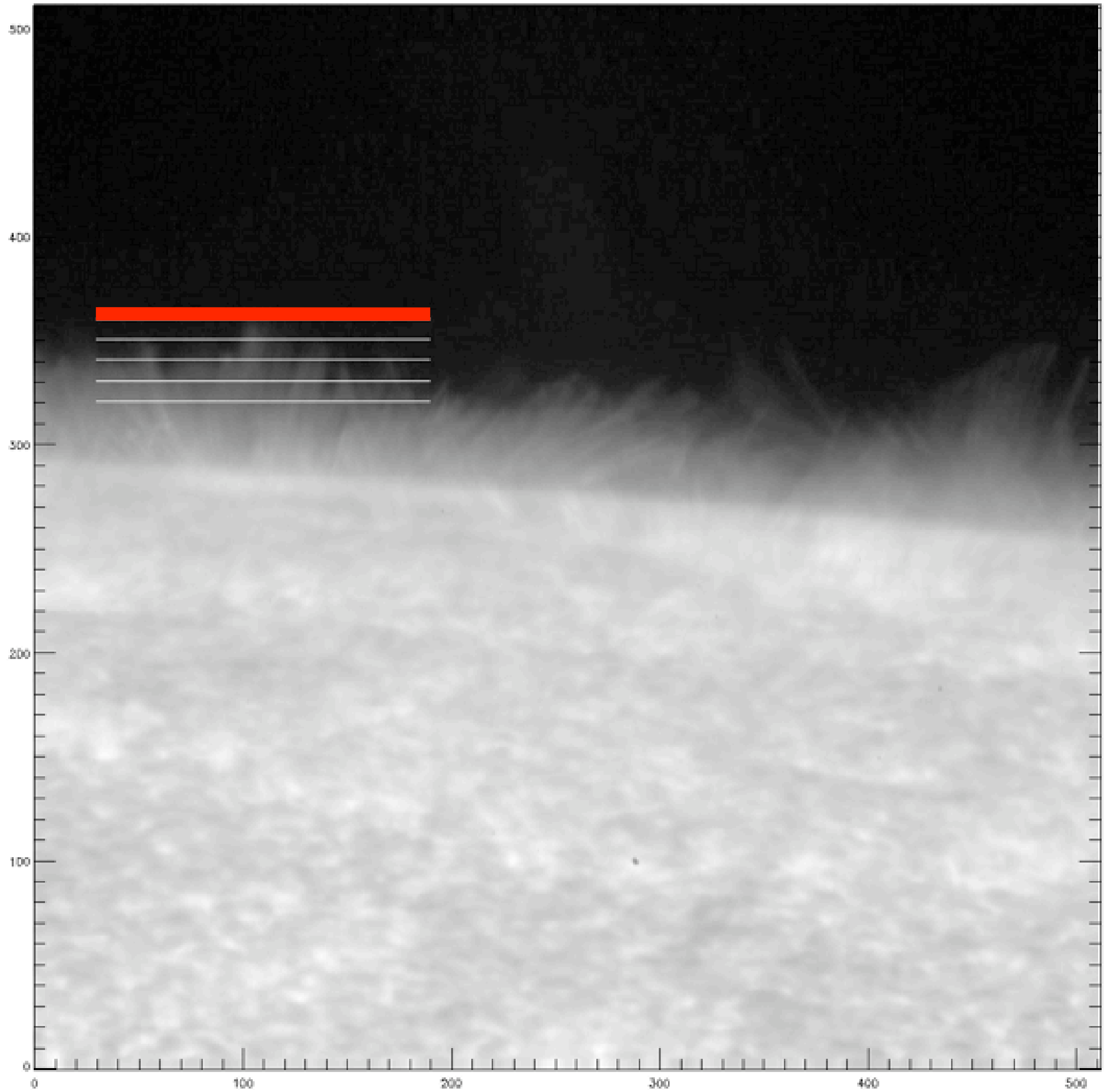
***Very general*: many inclined lines in xt-cuts of unsharp masked data**

Typically: thin straws moving laterally by 0.5 Mm, at ~10-25 km/s

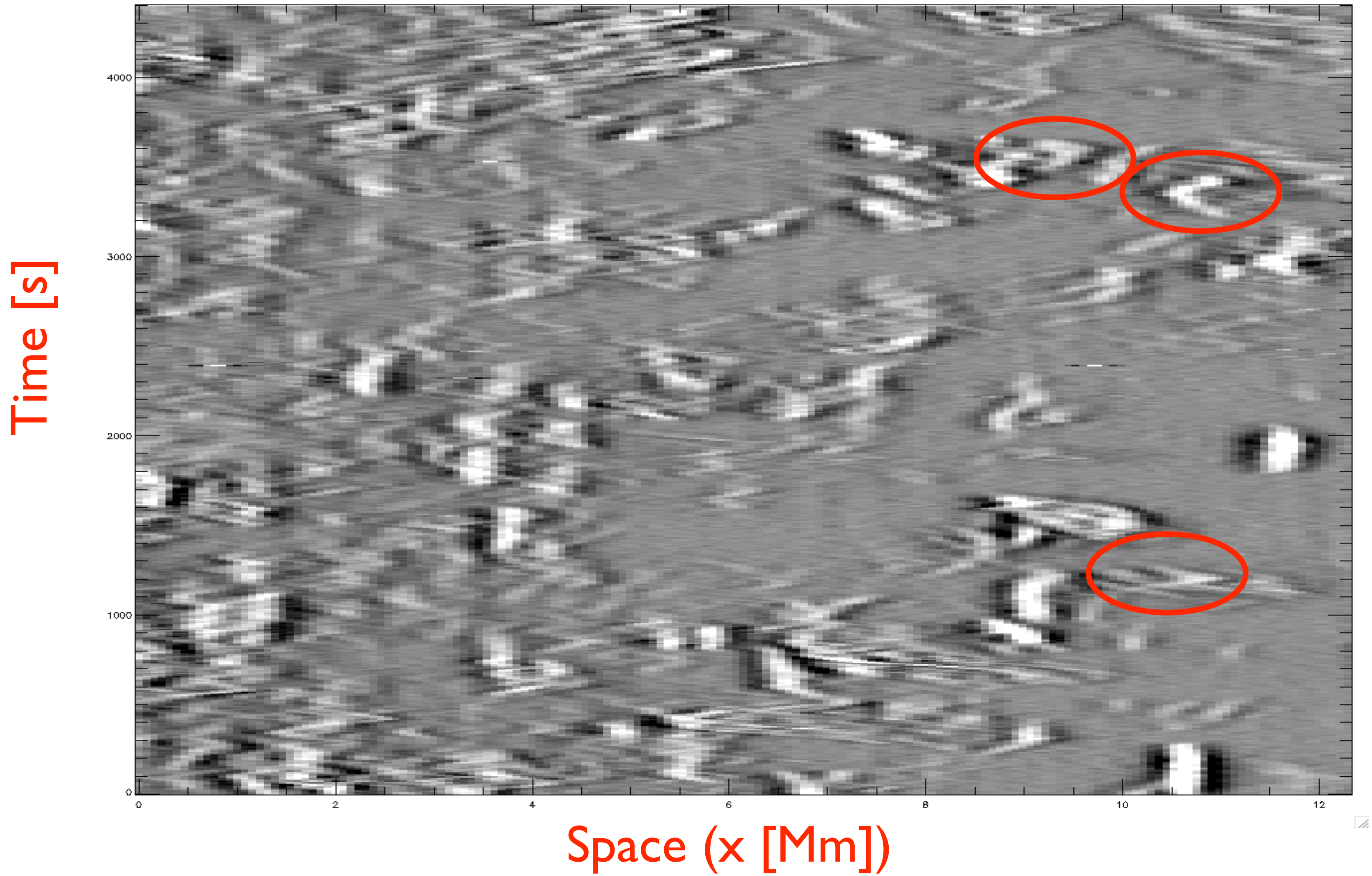
Superposition of many straws leads to large-scale criss-cross pattern



Less superposition at greater heights

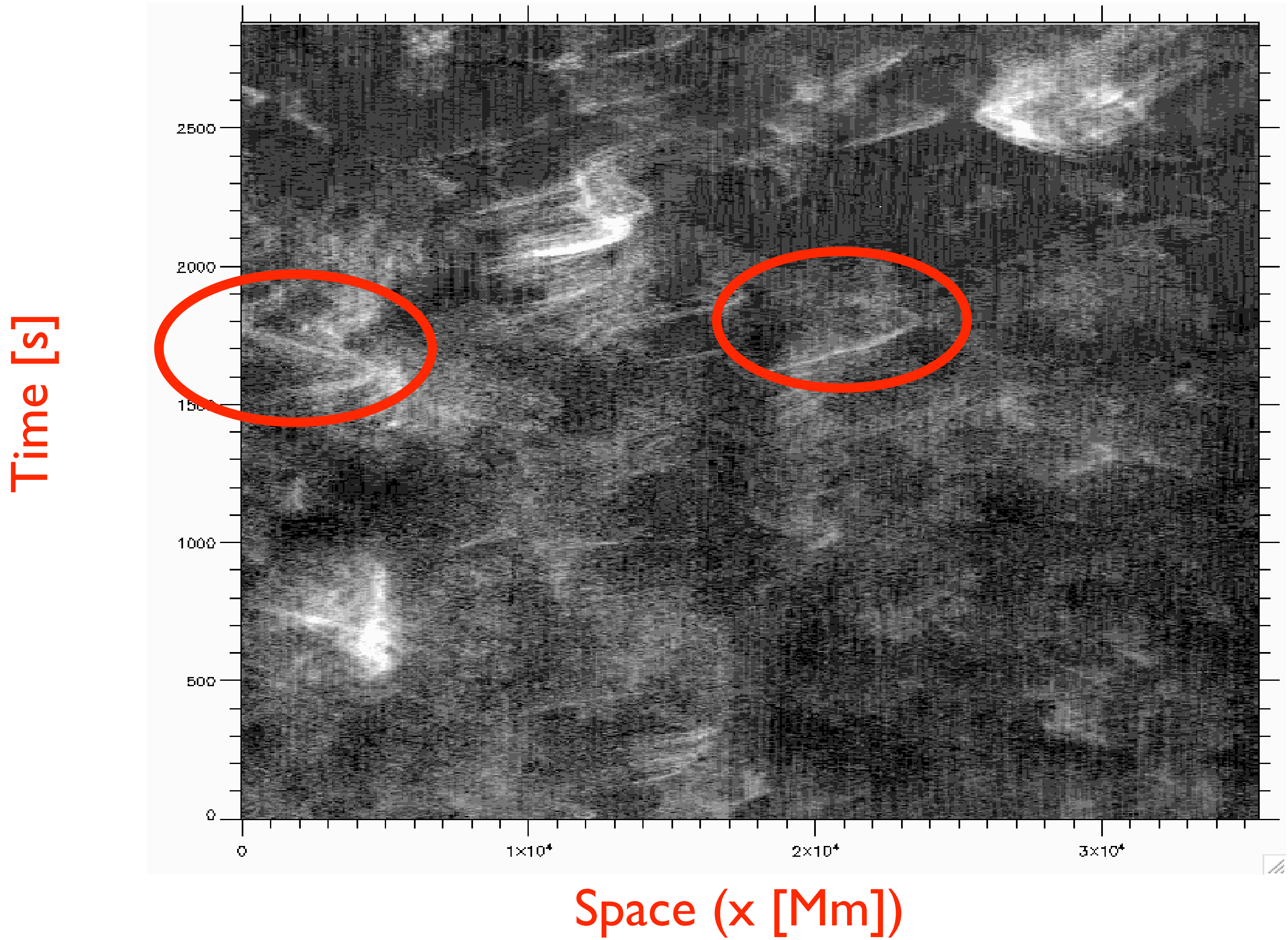


Fewer lines, and more swings at greater heights
(“v” shaped because of aspect ratio of xt-plot)



At greater heights: less superposition, unsharp masking unnecessary

Many half and some full swings with periods of 150-400 s



What's going on?

Chromosphere permeated by Alfvén waves
with periods longer than lifetimes
of dominant chromospheric features

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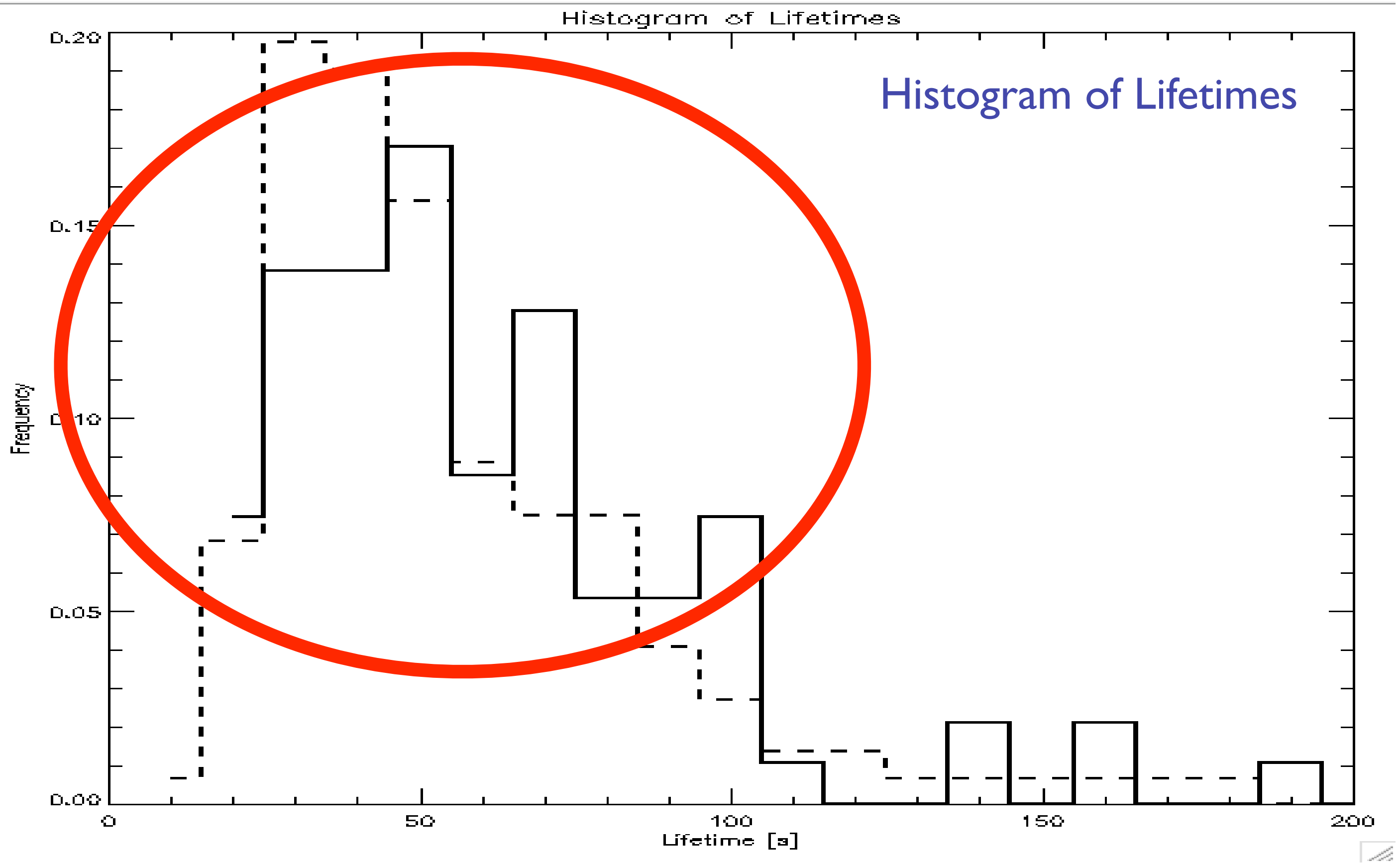
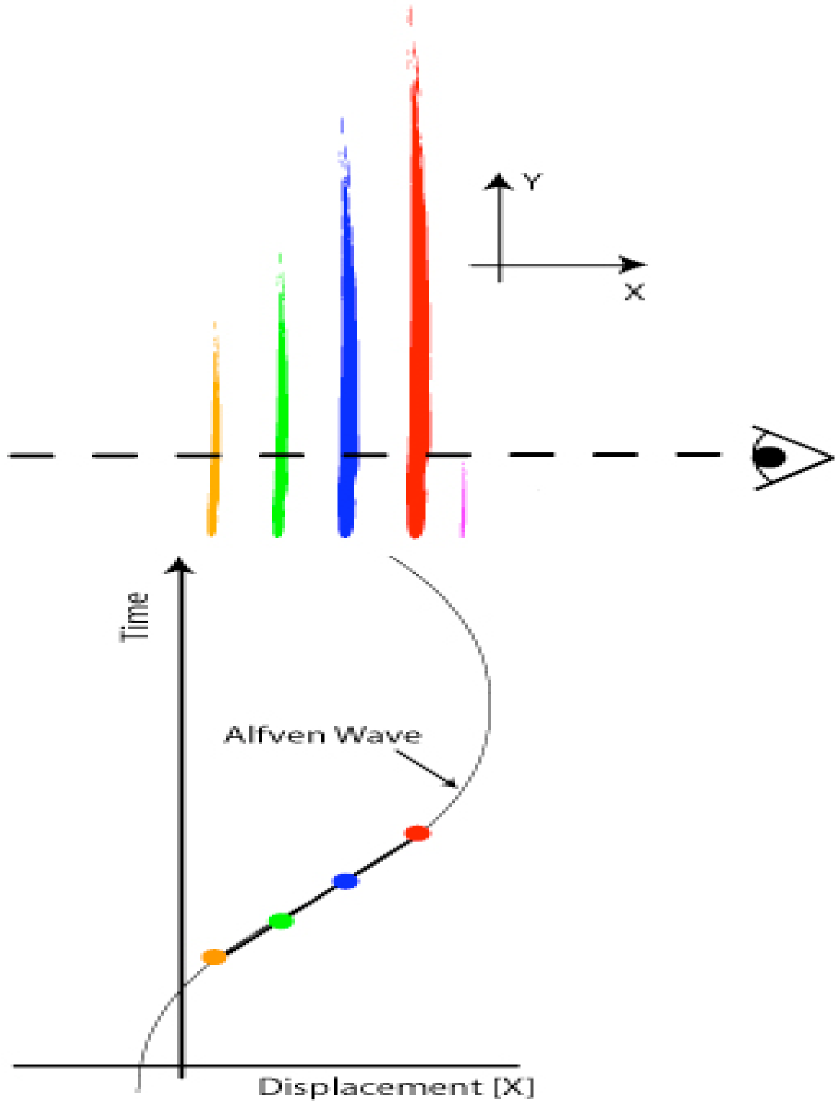


Ca II limb features short-lived: 10-100 s with some up to 300 s



The effects of the waves are only visible for a short time since the tracers of the magnetic field (jets/straws) have lifetimes << wave period.

The superposition of many weak, thin jets leads to criss-cross pattern of straight lines in xt-plots.

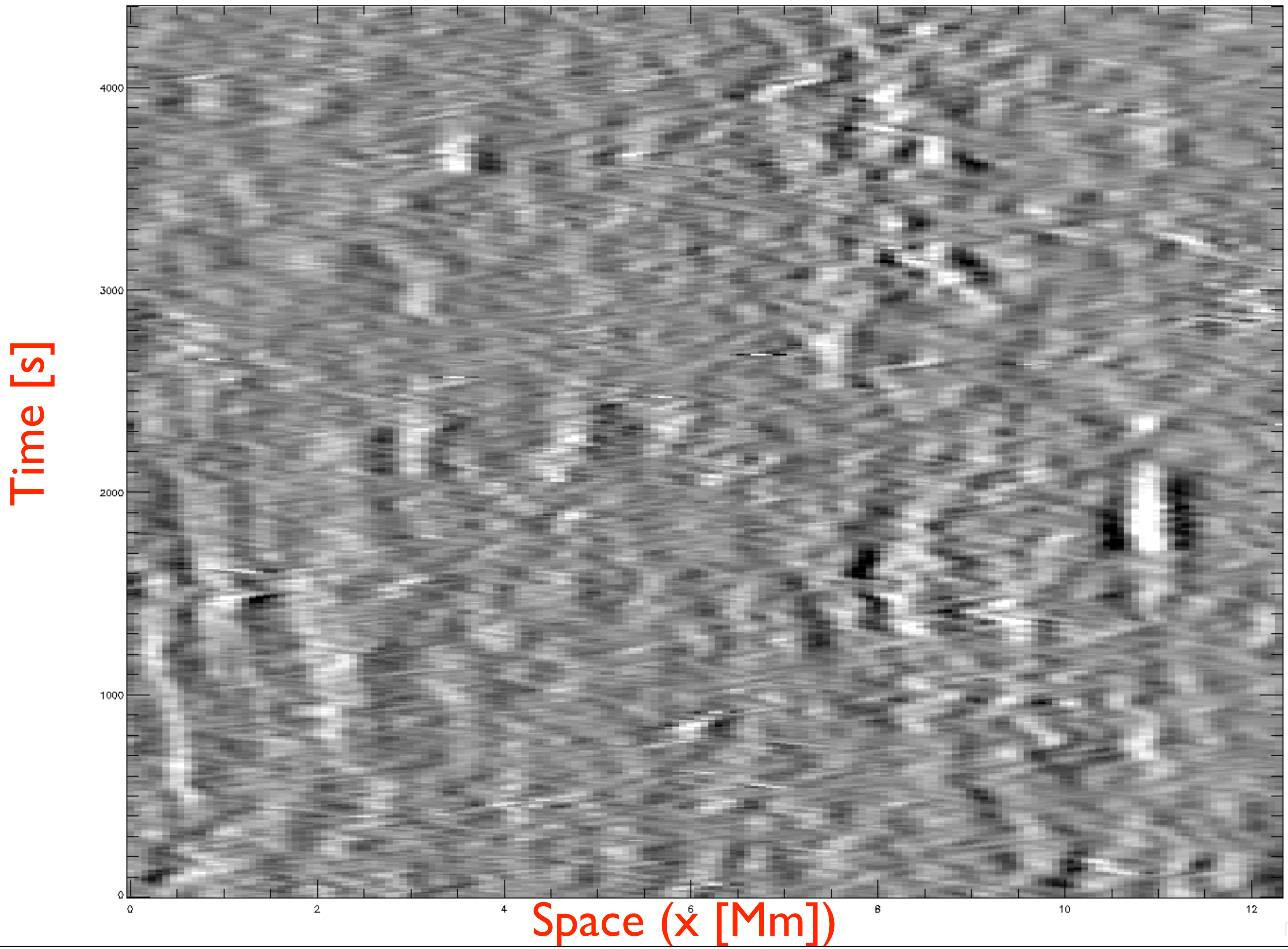
Monte Carlo simulations confirm this scenario

1. Sprinkle "straws" randomly (uniformly) in time and space.
2. Random uniform distribution of Straw Lifetimes: 10-60 s
3. Equal intensity for all straws

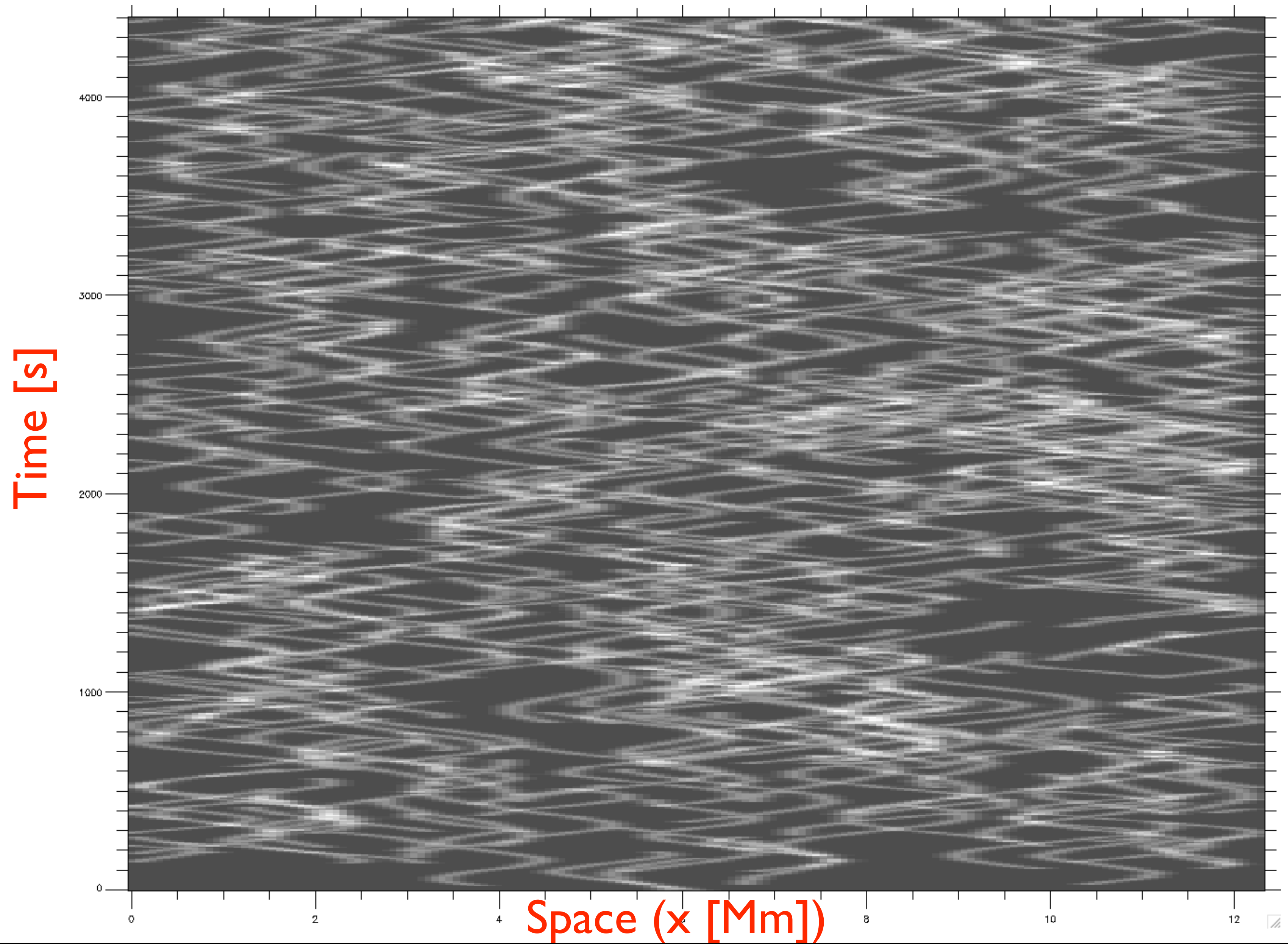
4. Apply transverse displacement from Alfvén waves to them.
5. Use random uniform distribution of Periods: 150-350 s
6. Random gaussian distribution of Amplitudes: 20+-5 km/s
7. Random uniform distribution of Phases
8. Random uniform distribution of Polarization Angles

9. Smear to spatial and temporal resolution of data

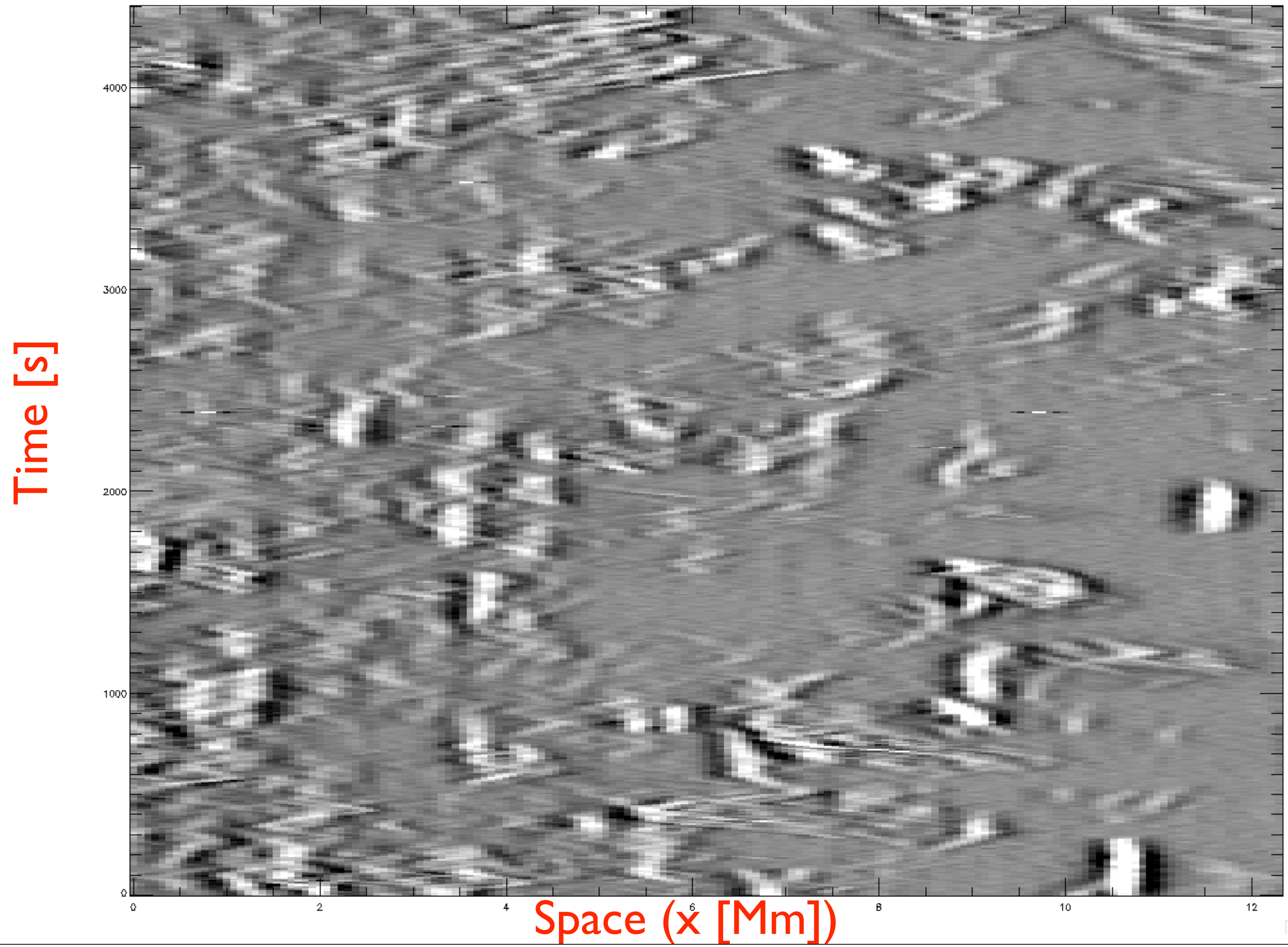
Unsharp masked observations at low heights



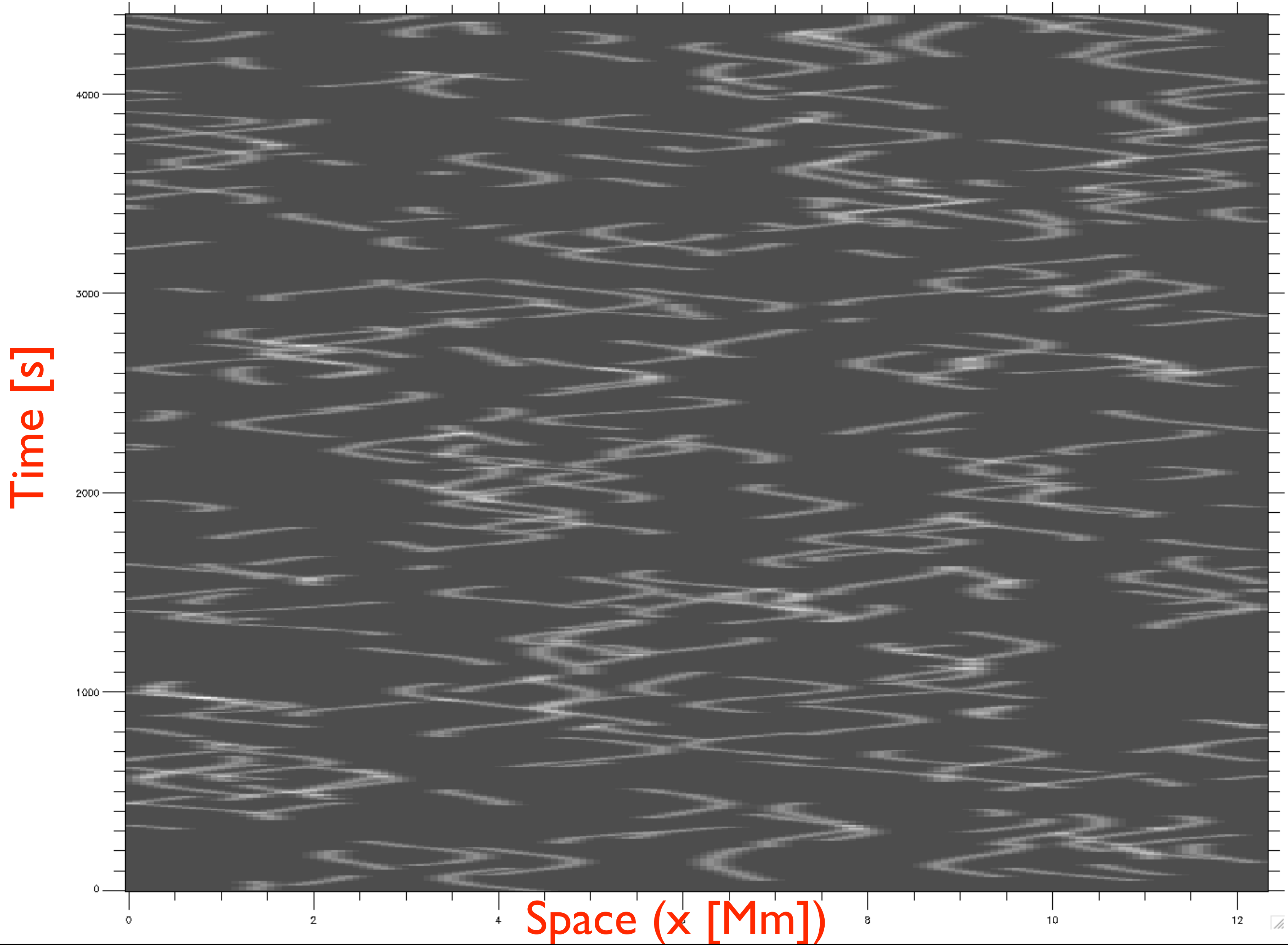
Simulated data is similar to obs: many straight lines + superposition



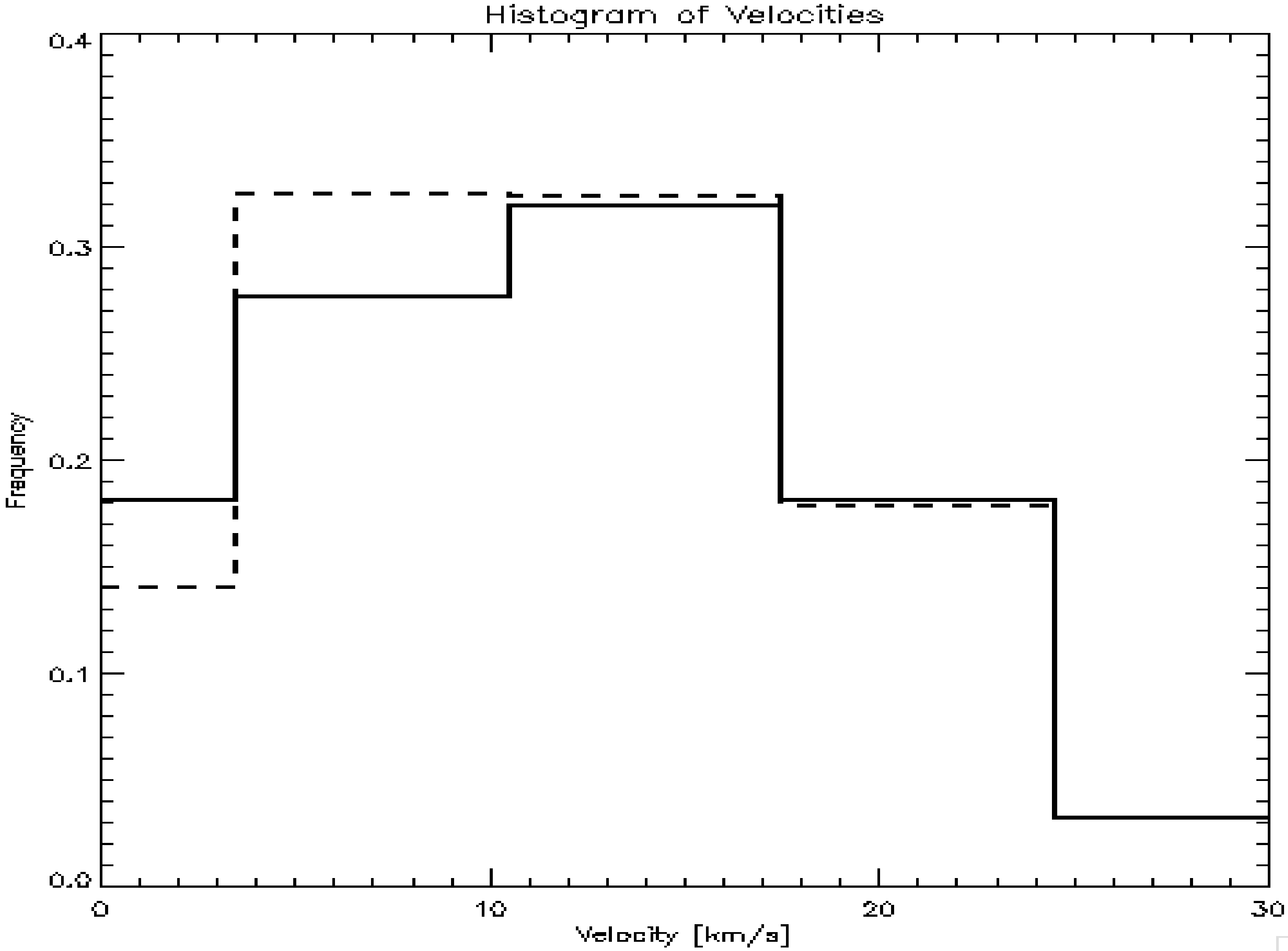
Unsharp masked observations at greater heights



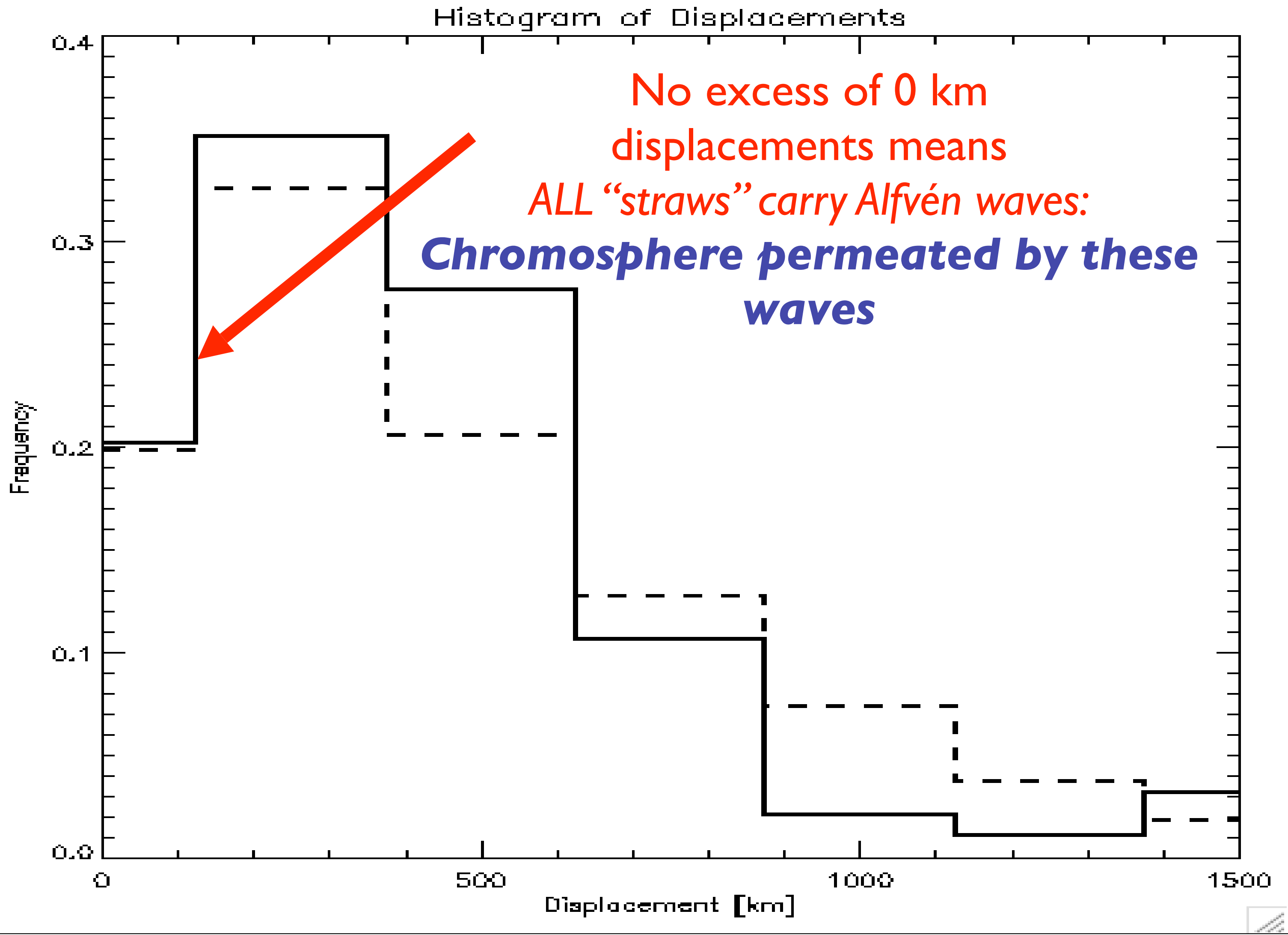
Simulated data similar to obs: lots of swings and less superposition



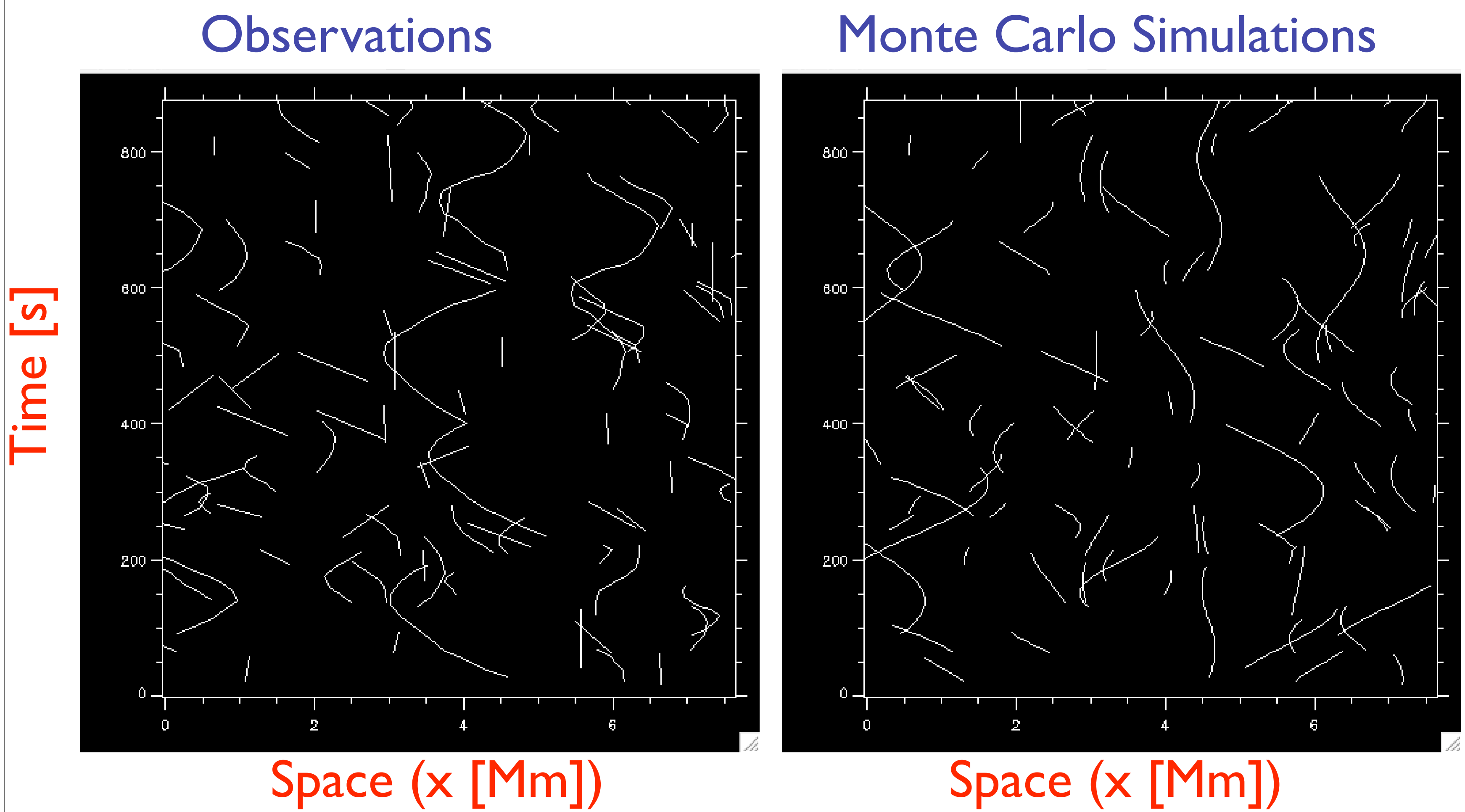
Monte Carlo simulation (dashed line) reproduces observed distribution (full line) of transverse velocity amplitude



Monte Carlo simulation (dashed line) reproduces observed distribution (full line) of transverse displacements



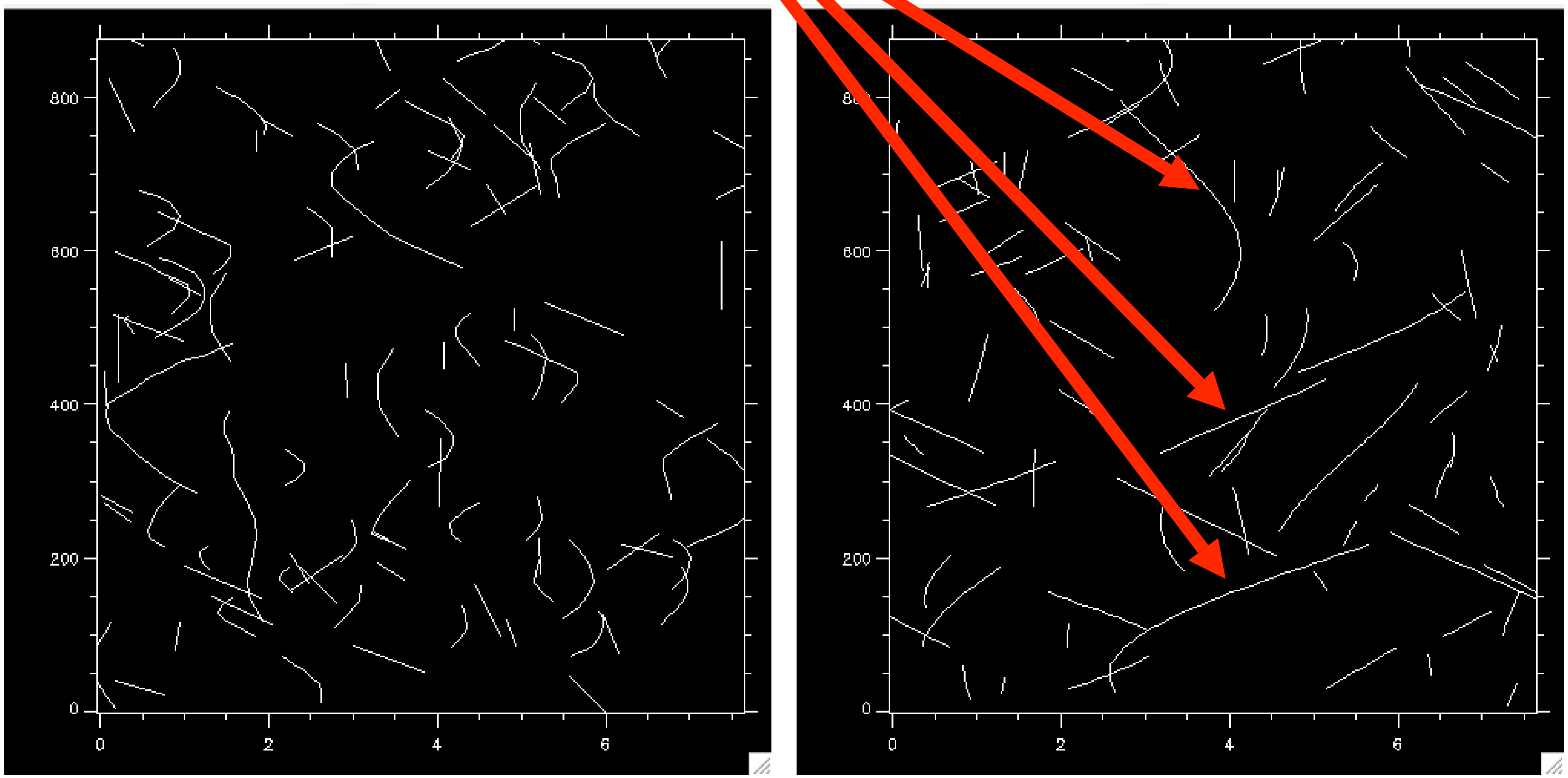
Period more difficult to determine, but MC sims fit data well for 150-350 s periods.



High periods (>500 s) would show longer paths than observed

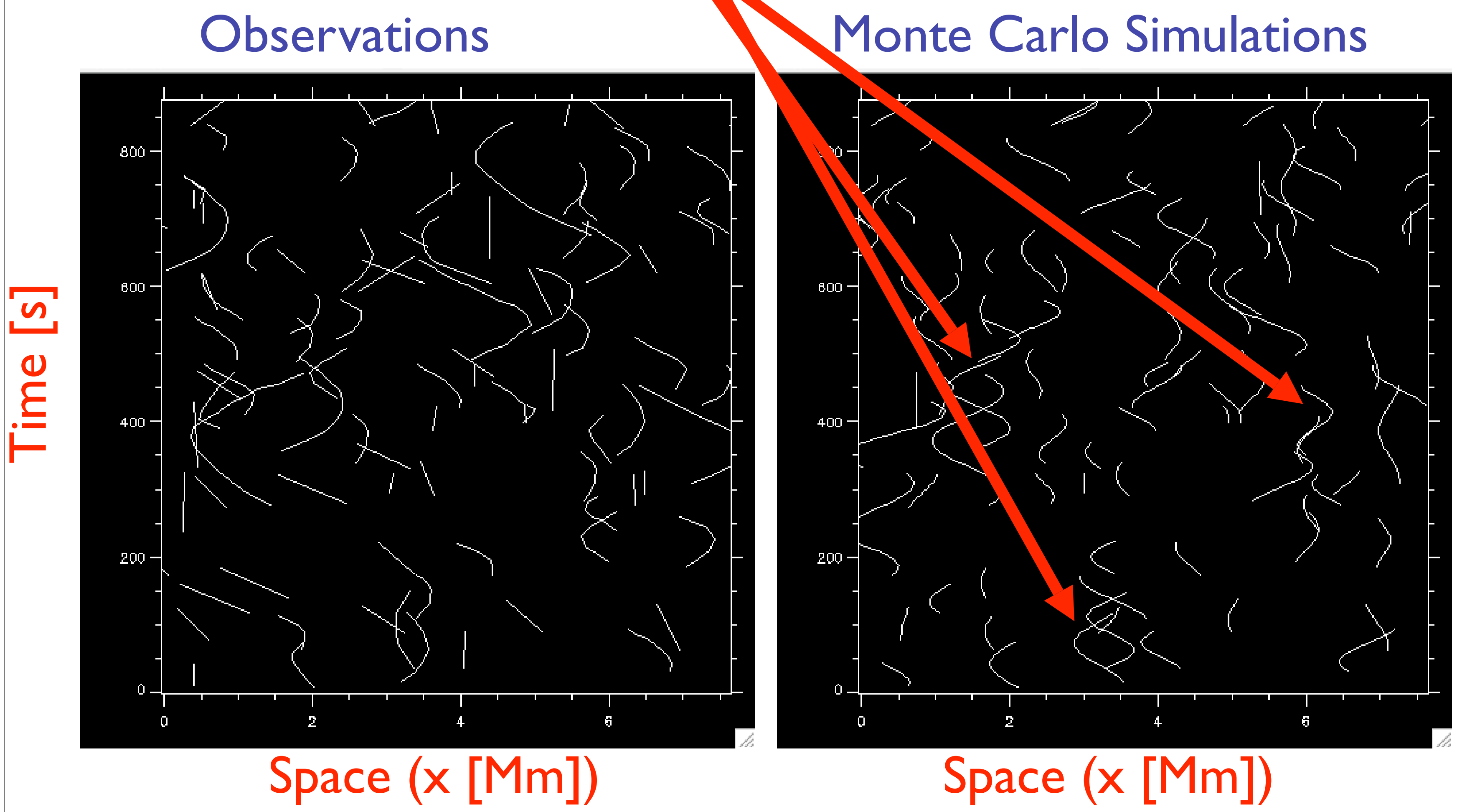
Observations | Monte Carlo Simulations

Time [s]



Space (x [Mm]) | Space (x [Mm])

Short periods (50-150 s) would show more swings than observed



How do these waves get generated?

1. Buffeting of magnetic elements in photosphere (Cranmer & van Ballegooijen, 2006 predict 5-20 km/s amplitudes in chromosphere)?

2. Mode-coupling of 3-5 min slow-mode magnetoacoustic shock waves (which drive type I spicules) at $\beta=1$ may explain periods?

3…. ?

How much energy flux into solar wind/corona?

Probably a lot: 20 km/s means they are strong waves

Very Conservative Estimate:

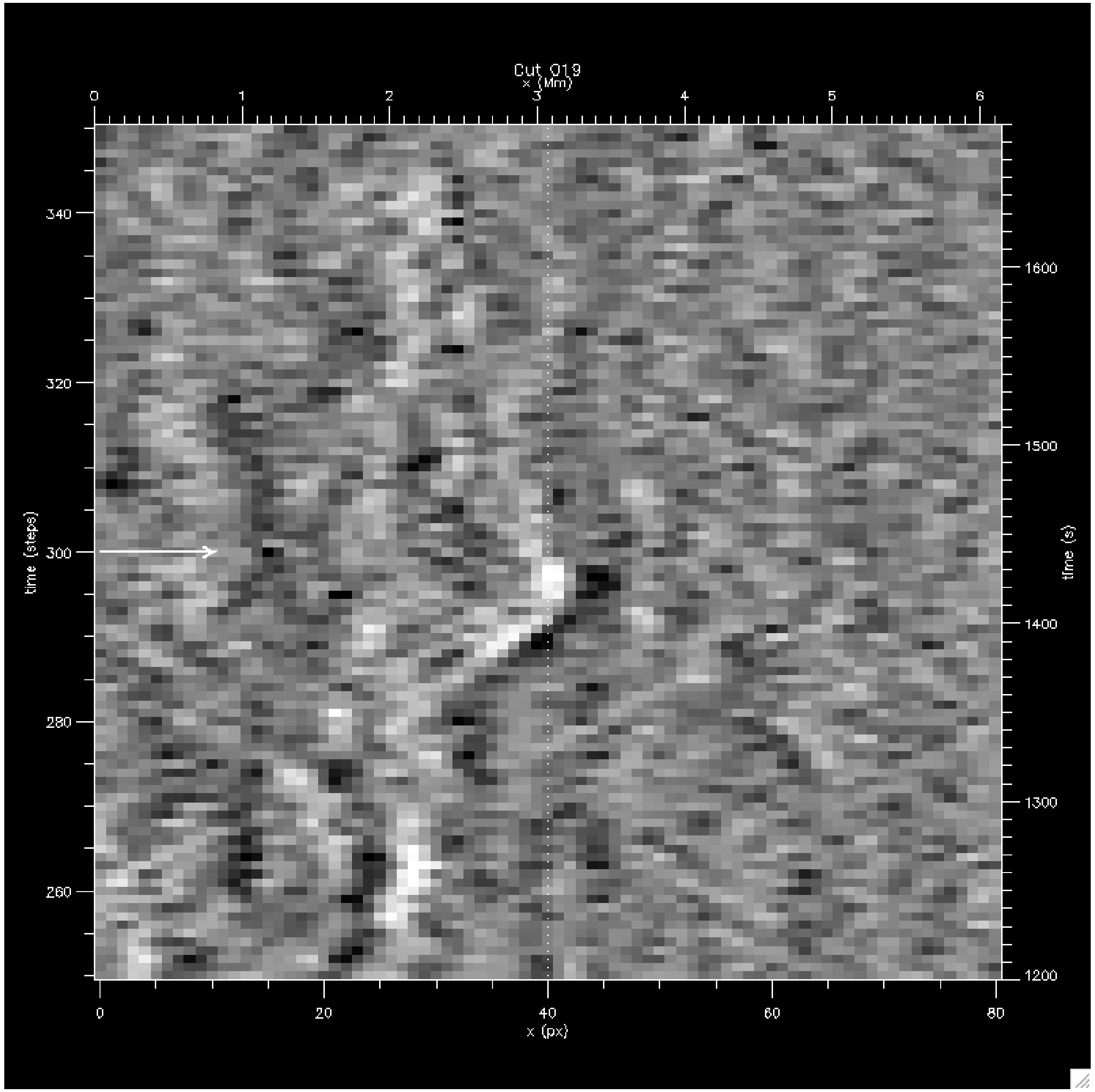
1. assume low "spicule" density of 10^{10} cm^{-3} (Beckers 5-10 higher)
2. measure propagation speed of ~50+ km/s)
3. measure amplitudes of 20 km/s

Chromospheric Flux ~ 4 kW (4 10^6 erg/cm^2/s)

4. transmission to corona 1-10% (Hollweg, 1984)

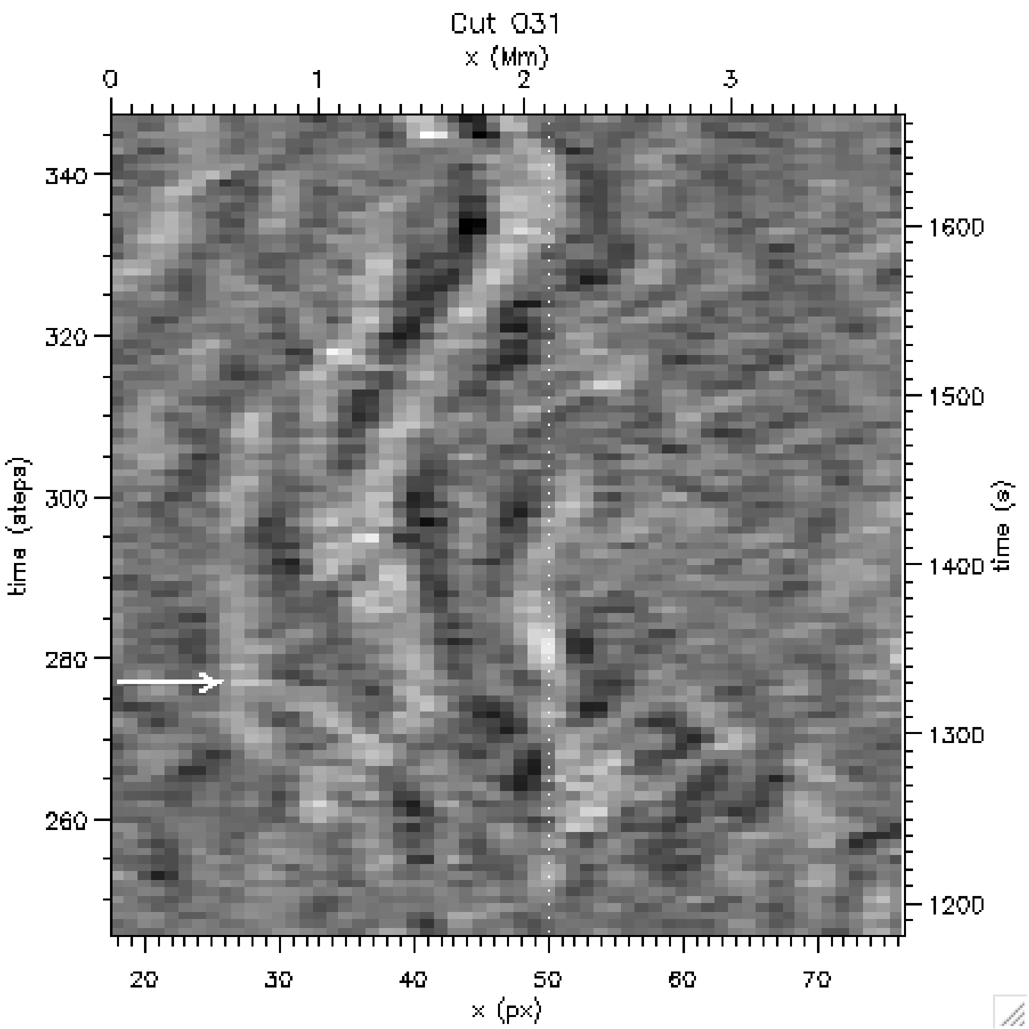
Coronal/Solar Wind Flux ~ 100 W (10^5 erg/cm^2/s)]
= Enough to drive solar wind with low-frequency Alfven waves (Cranmer & van Ballegooijen, 2005)?

Do we see evidence of propagation/reflection?



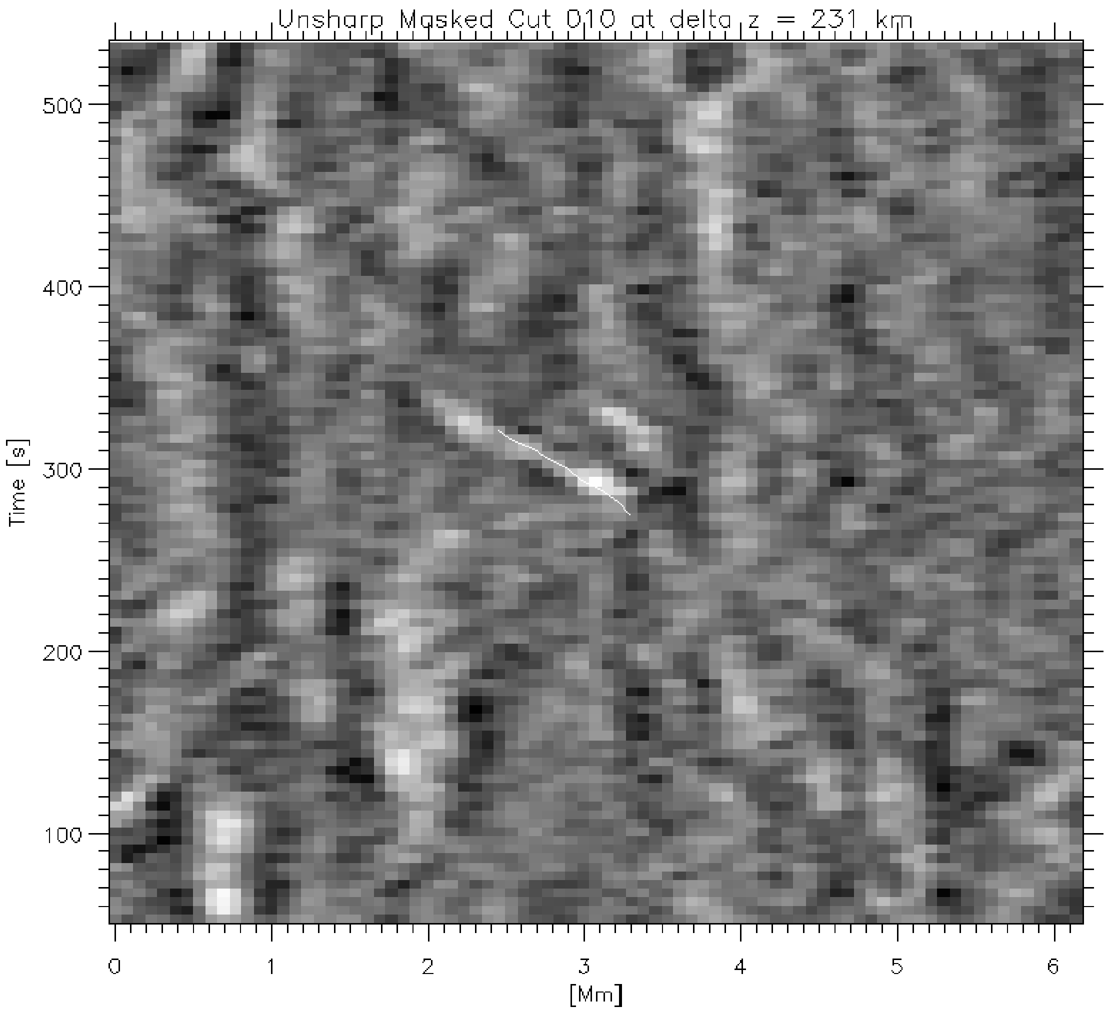
Height difference=384 km
Time resolution=4.8 s
Propagation > 75 km/s?
(typical case)

Do we see evidence of propagation/reflection?



Height difference=690 km
Time resolution=4.8 s
Propagation ~ 140 km/s?

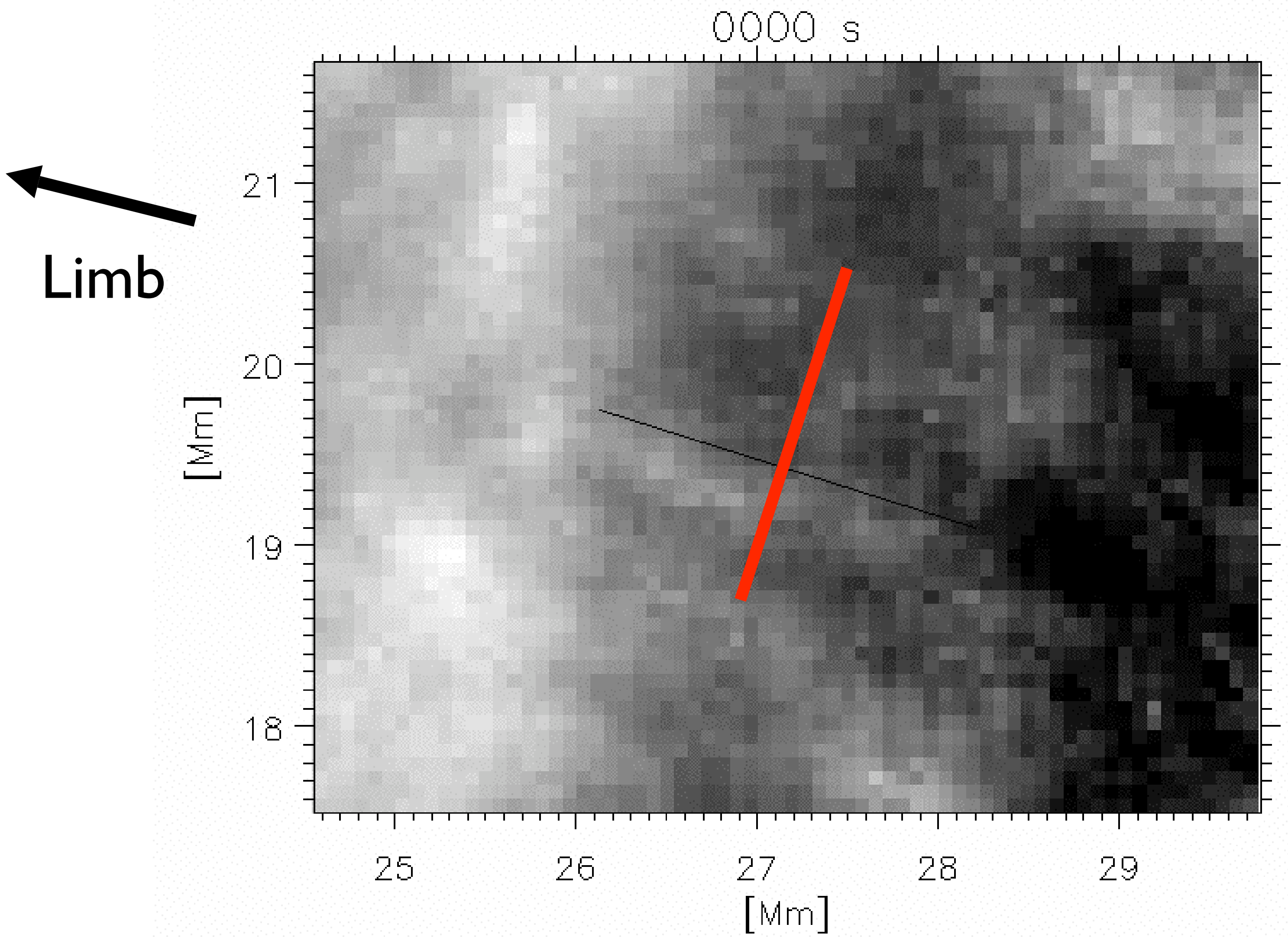
Reflection makes "propagation speed" estimates problematic...



Increased amplitude at greater heights?

Upward propagation first, Downward propagation later?

"Height Profile of transverse displacement" skewed



Mix of Upward and Downward propagating waves

Form "simulated" straw with

v_{straw} ~ 70 km/s

lifetime ~ 50 s

undergoing Alfvenic motion with

v_{alfven} ~ 50 km/s

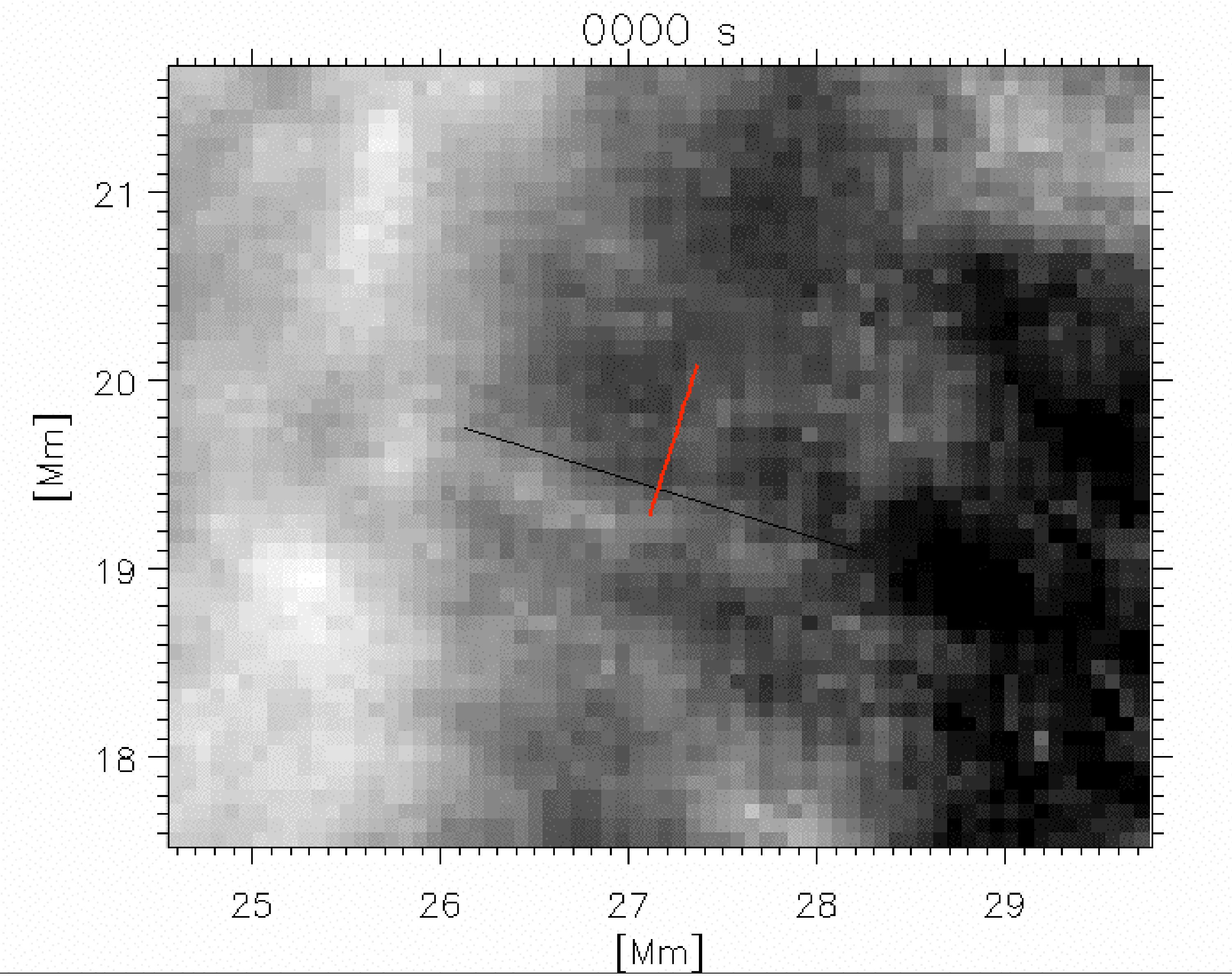
Period ~ 180 s

$v_t = v_1 \sin(\omega t - kz) + v_2 \sin(\omega t + kz + \varphi)$

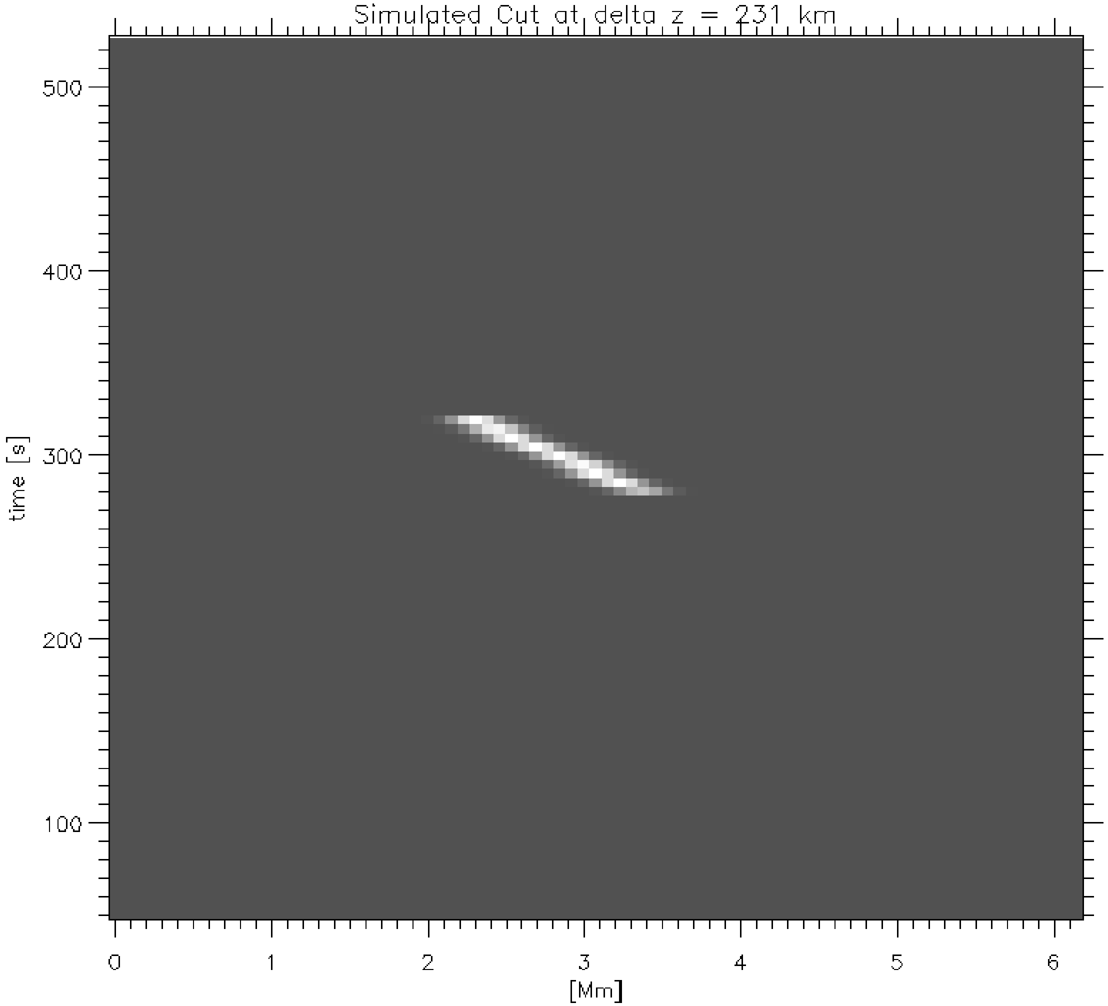
with $v_1 \sim v_2$ given strong reflection off TR

φ phase difference between waves

Mix of Upward and Downward propagating waves



Full Height Profile of Transverse Displacement Necessary



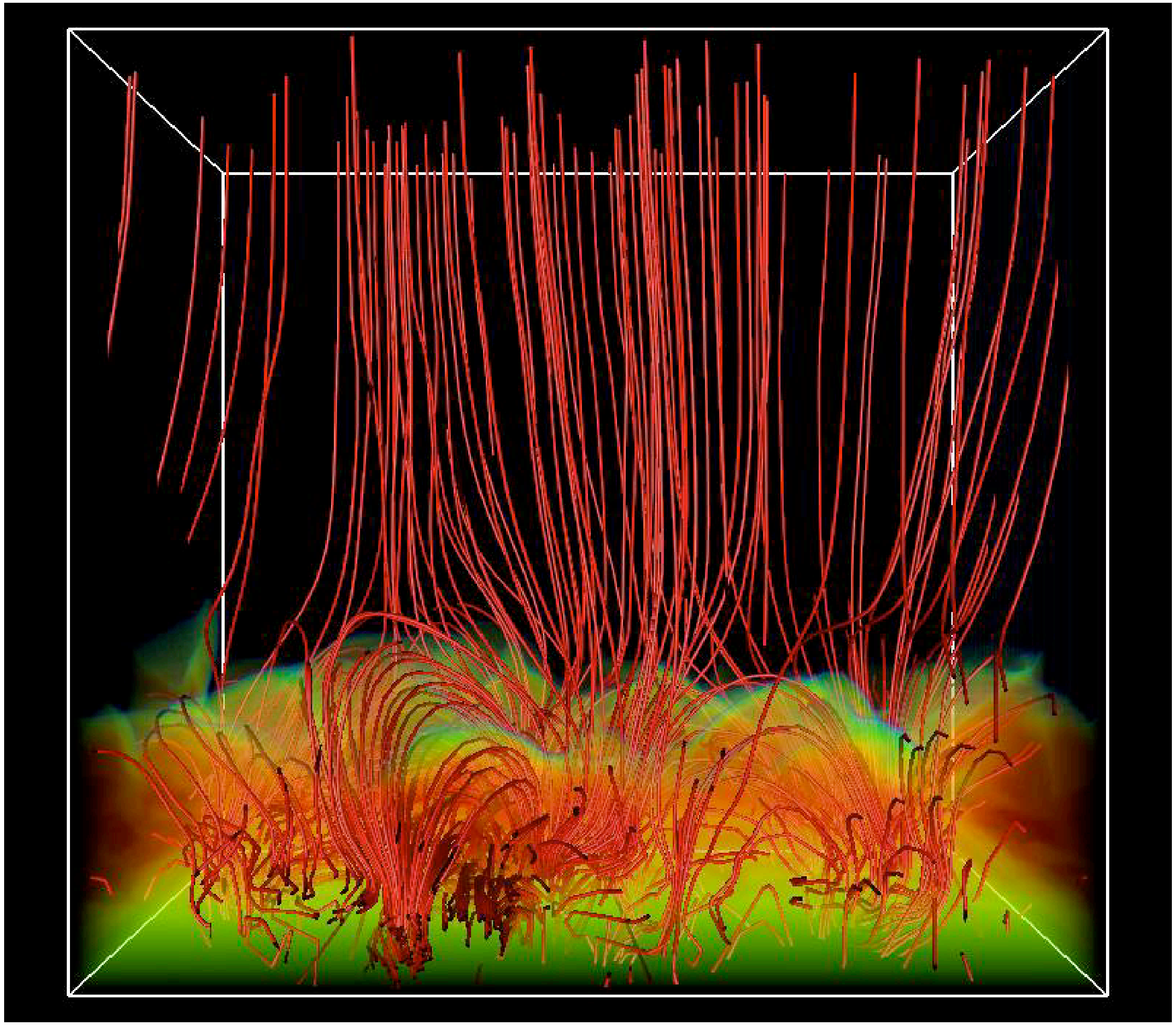
Many profiles indicate straightforward interpretation of "propagation" is difficult.

3D models from convection zone to corona

Hansteen 2004, Hansteen, Carlsson, Gudiksen 2007

- 16x8x12 Mm (2 Mm below, 10 Mm above z=0)
- Open boundaries
- Detailed radiative transfer along 48 rays
    - Multi-group opacities (4 bins) with scattering
- NLTE radiative losses in chromosphere (CaII, H)
- Optically thin losses in corona
- Conduction along field-lines
- Various initial magnetic field configurations
- No imposed driving (selfconsistent convection)

Generation/Transmission into corona can be studied using realistic 3D simulations

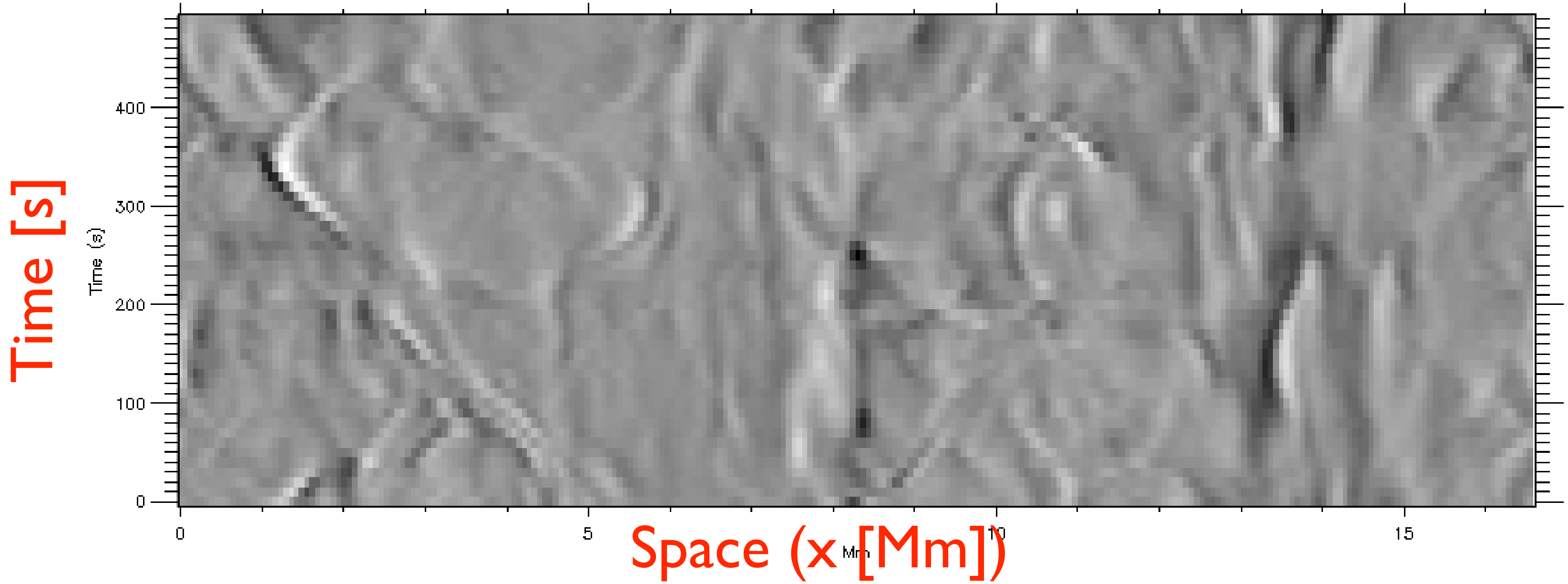


Red field lines

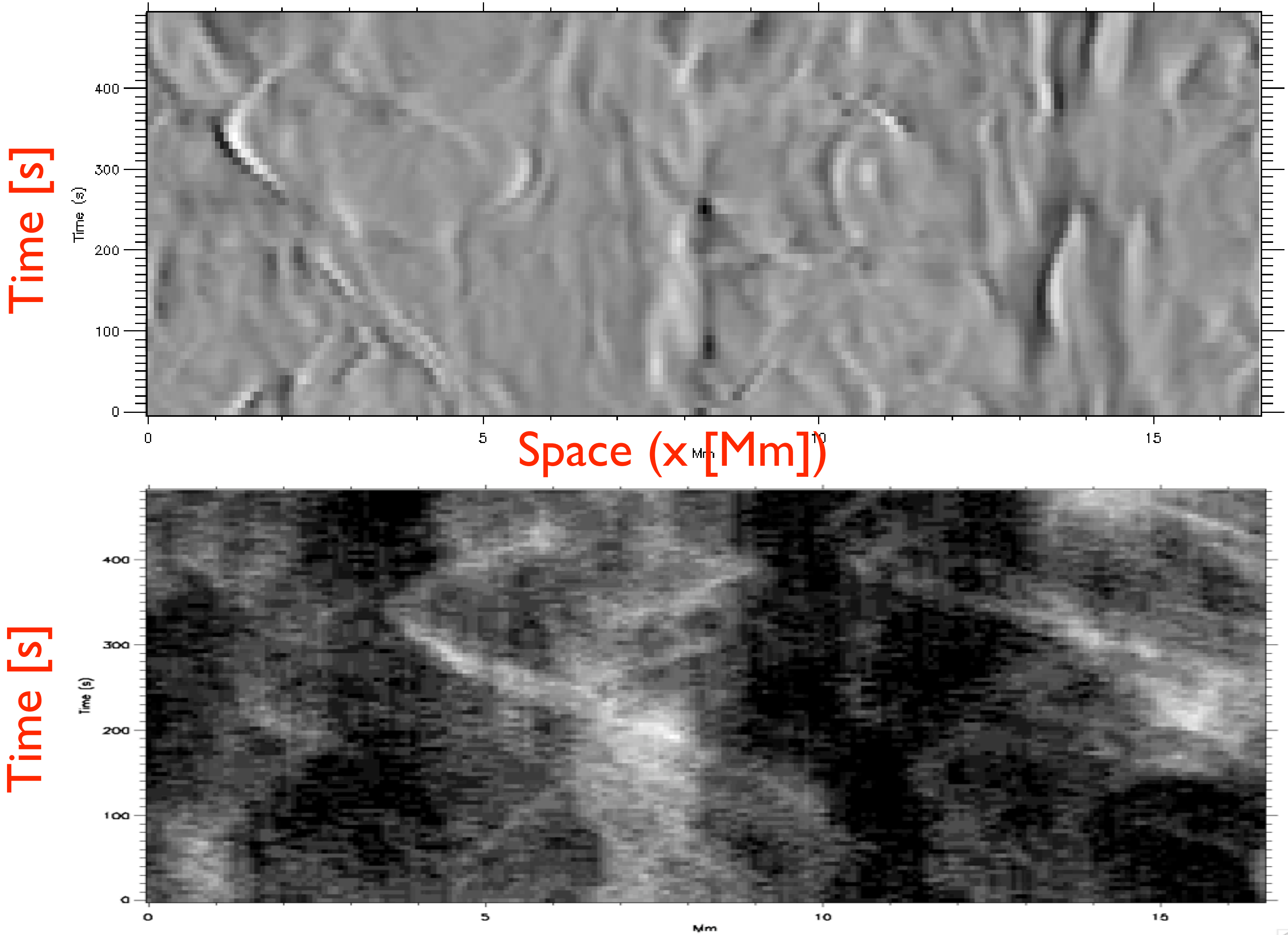
Coloring is temperature (red=chromosphere green/blue= TR)

Hansteen & Carlsson

3D simulations show ubiquitous Alfvén waves



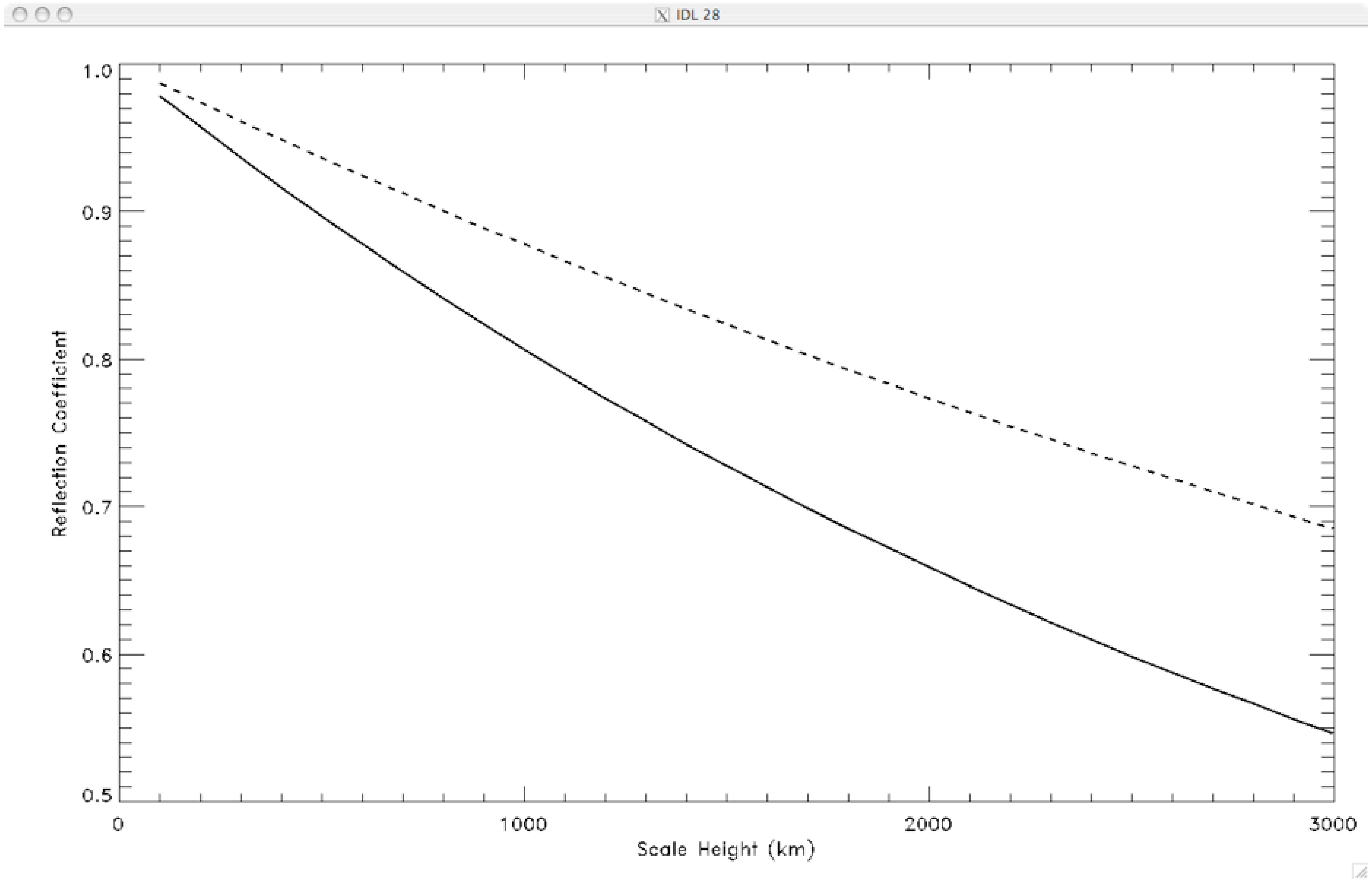
With similar periods/amplitudes as observations



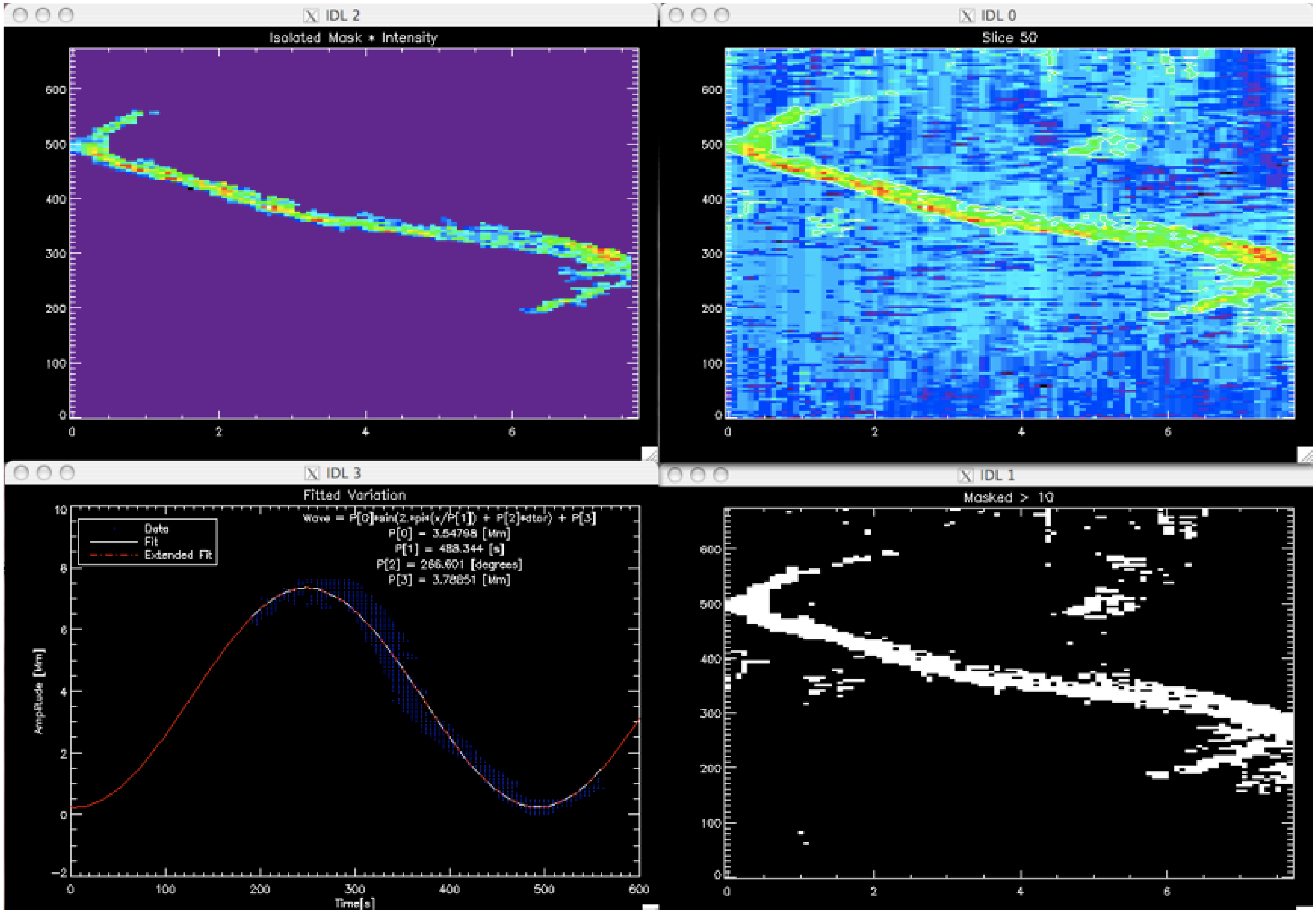
Conclusions

1. Most chromospheric features at CH/QS limb undergo significant transverse displacements
2. Displacements of order 0-1 Mm, with velocities 10-25 km/s
3. Driven by Alfven waves with periods of 150-400 s
4. Mix of upward and downward waves (i.e., significant reflection off TR?)
5. Despite reflection, large potential for high energy flux in corona of order 100 W/m^2 (10^5 erg/cm^2/s): enough to drive solar wind?

Reflection of upward traveling Alfven waves at TR



v_alfven exponential with height until corona (constant)
full line for P=180s, dashed for P=300 s


IDL 2
Isolated Mask * Intensity
IDL 0
Slice 50
IDL 3
Fitted Variation
Data
Fit
Extended Fit
Wave = P[0]*sin(2.*pi*(x/P[1]) + P[2]*dtor) + P[3]
P[0] = 3.54798 [Mm]
P[1] = 488.344 [s]
P[2] = 266.601 [degrees]
P[3] = 3.78851 [Mm]
Amplitude [Mm]
Time[s]
IDL 1
Masked > 10